Presentation of PERL Injector R&D

1. Overview PERL Injector R&D (10 minutes) X.J.Wang
2. Laser and Cathode for PERL (25 minutes) Triveni
3. DC Option Studies for PERL (15 minutes) F. Zhou
4. 433 MHz and B-factory based Injector (20 minutes) – I. Ben-Zvi
5. L-band PERL Injecotr (15 minutes) xj&Chang
6. Future R&D Plan for PERL Injector (10 minutes) xj

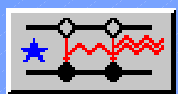
Overview of PERL Injector R&D

- *X.J. Wang*

- Presented at NSLS PERL Review
- April, 10, 2001

- **Introduction.**
- **PERL Injector R&D plan**
- **PERL Injector parameters.**
- **Presentations.**
- **Summary and Future R&D direction.**

Introduction - Synchrotron Radiation: Where are we going?



Laser revolutions:

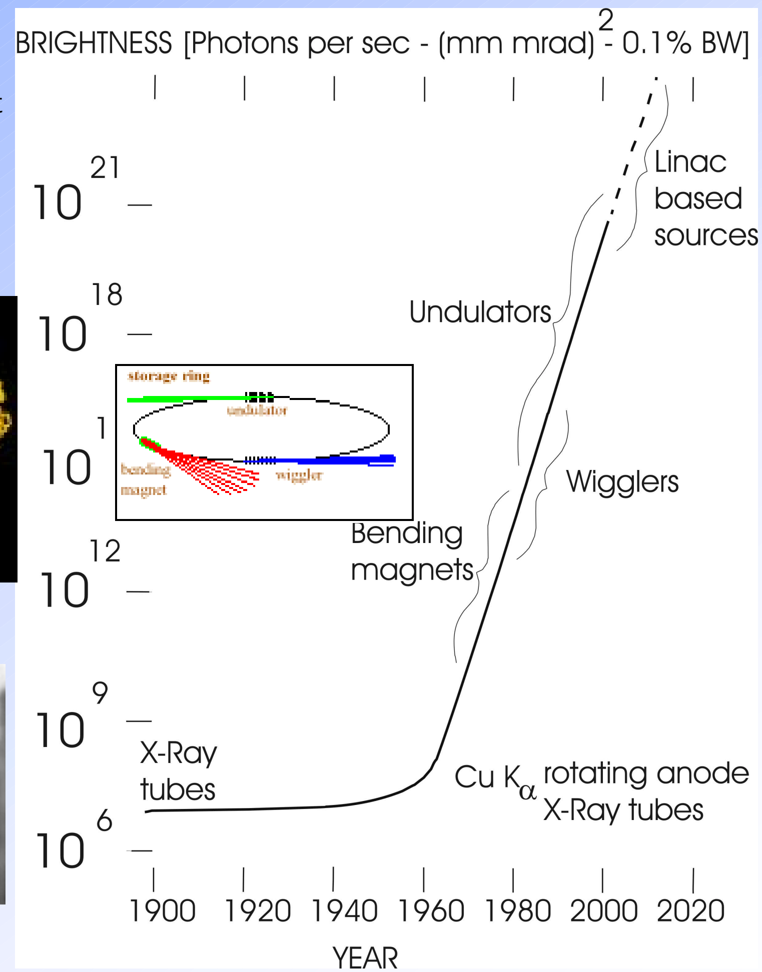
- High resolution spectroscopy
- Short pulse (dynamics)

Large Ribosomal Subunit at 2.4 Å resolution, N. Ban et al. Science, 289, 905 (2000)

- X-rays due next!
- How do we do it?

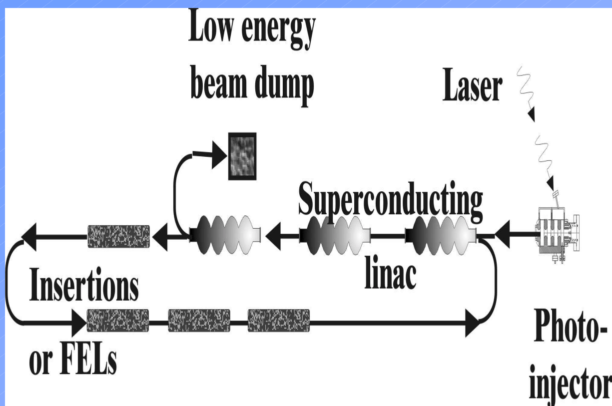
  The answer may be

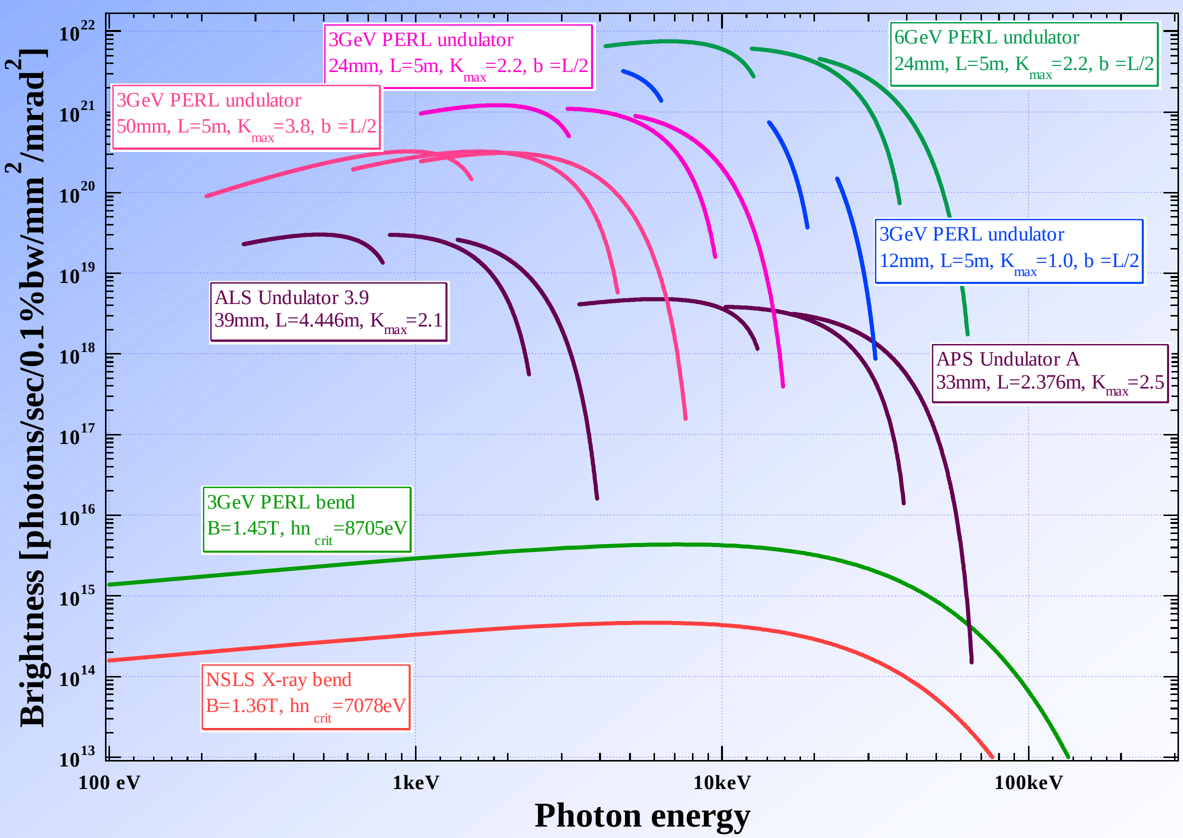
  linac based sources.



- •Ultrafast Structural Dynamics
- •Ultrafast Processes & Time-Dependent Measurements
- •Ultrahigh Spatial Resolution
- •Microscopy
- •Coherent X-ray Scattering
- •Ultrasmall Membrane Proteins

Introduction - PERL Brightness





Even the spontaneous emission is outstanding!

Injector determines the beam quality!!

NSLS PERL INJECTOR R&D
November, 2000

1. Near term plan:
    A-1: Cost estimate:
    A. Parameters Studies:
        1. Laser system: pulse length, power; rep. Rate; Cathode material; jitter (timing, energy, centroid).
        2. Injector linac (work with beam dynamics group): final energy, charge, bunch length (longitudinal emittance), emittance.
        3. Configuration: DC and RF guns, warm and superconduction cavities; compression schemes; dual injectors, beam diagnostics.
    B. Beam dynamics studies:
        1. 433 Mhz/B-factory based RF gun simulation:
        2. L-band RF gun simulation
        3. DC gun simulation:

	DC	433.3 Mz	L-band	other
Duty factor (%)	100	25	1	
Cathode field (MV/m)	10 M	26	50	
Gun exit energy (MeV)	0.3		5.7	
Charge (nC)	0.075/0.150	1	1.0	
Power (kW)		600	4500	
Injector energy(MeV)	10	5	20	

    C. Visitors and Visiting:
2. Mid-term:
    A. Settle a set of beam parameters, detail beam dynamics studies.
    B. Initial engineering studies.
    C. Cathode studies: set up a test stand to studies various high QE material. Exotic electron emission studies.

3. Long term: Construction of injector test stand.

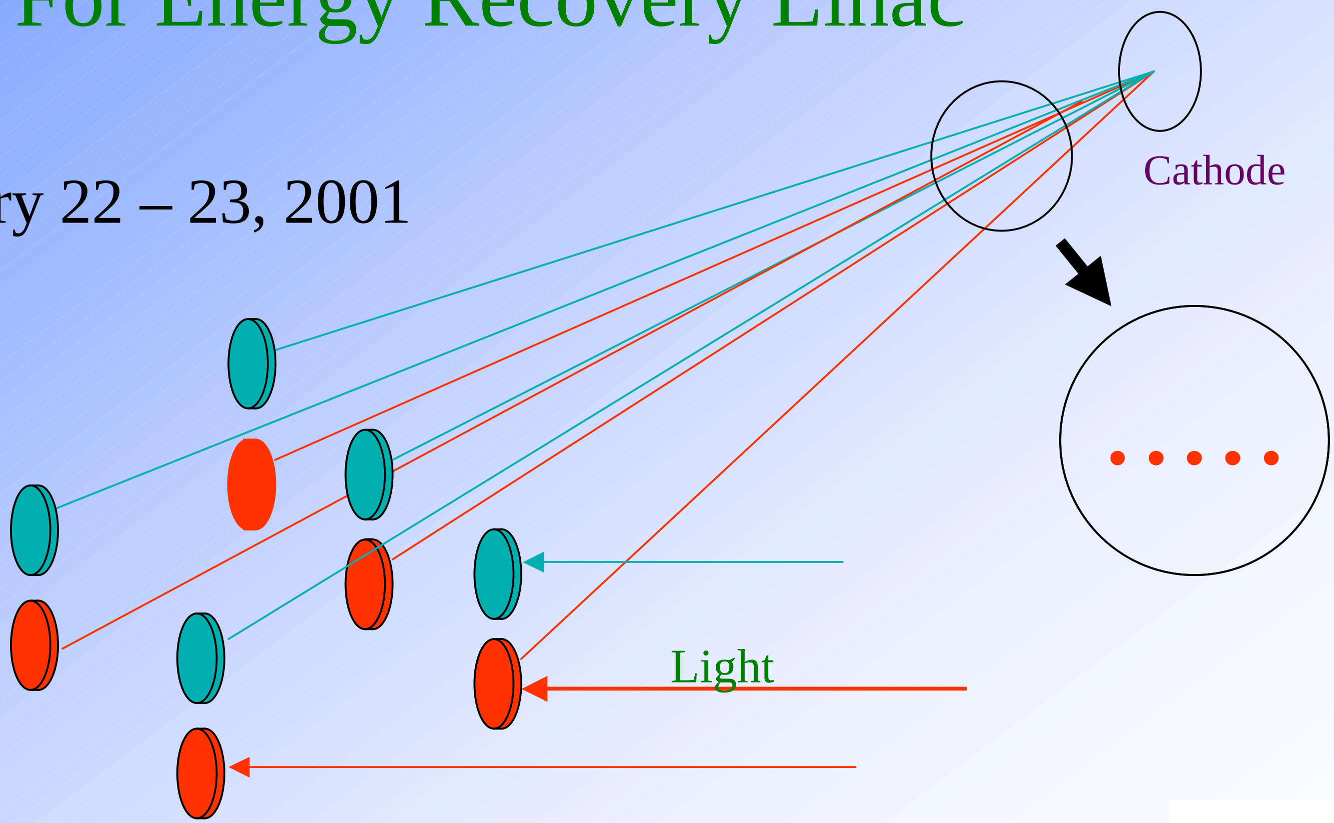
PERL Injector parameters

- Compare all approaches at 25 MeV final energy.
- Charge per bunch: 0.15 nC or 0.45 nC
- High rep rate: 1300 or 433 MHz
- Normalized RMS emittance: ~1 mm-mrad
- Longitudinal RMS emittance: 3 ps * 23.2 KeV @ 25 MeV
- Uptime: 24 hrs/day, 25 days/month, 11 months/year

National Synchrotron Light Source

Proceeding of Workshop on Photo-injector For Energy Recovery Linac

January 22 – 23, 2001



Brookhaven Science Associates
U.S. Department of Energy

BROOKHAVEN
NATIONAL LABORATORY

Presentation of PERL Injector R&D

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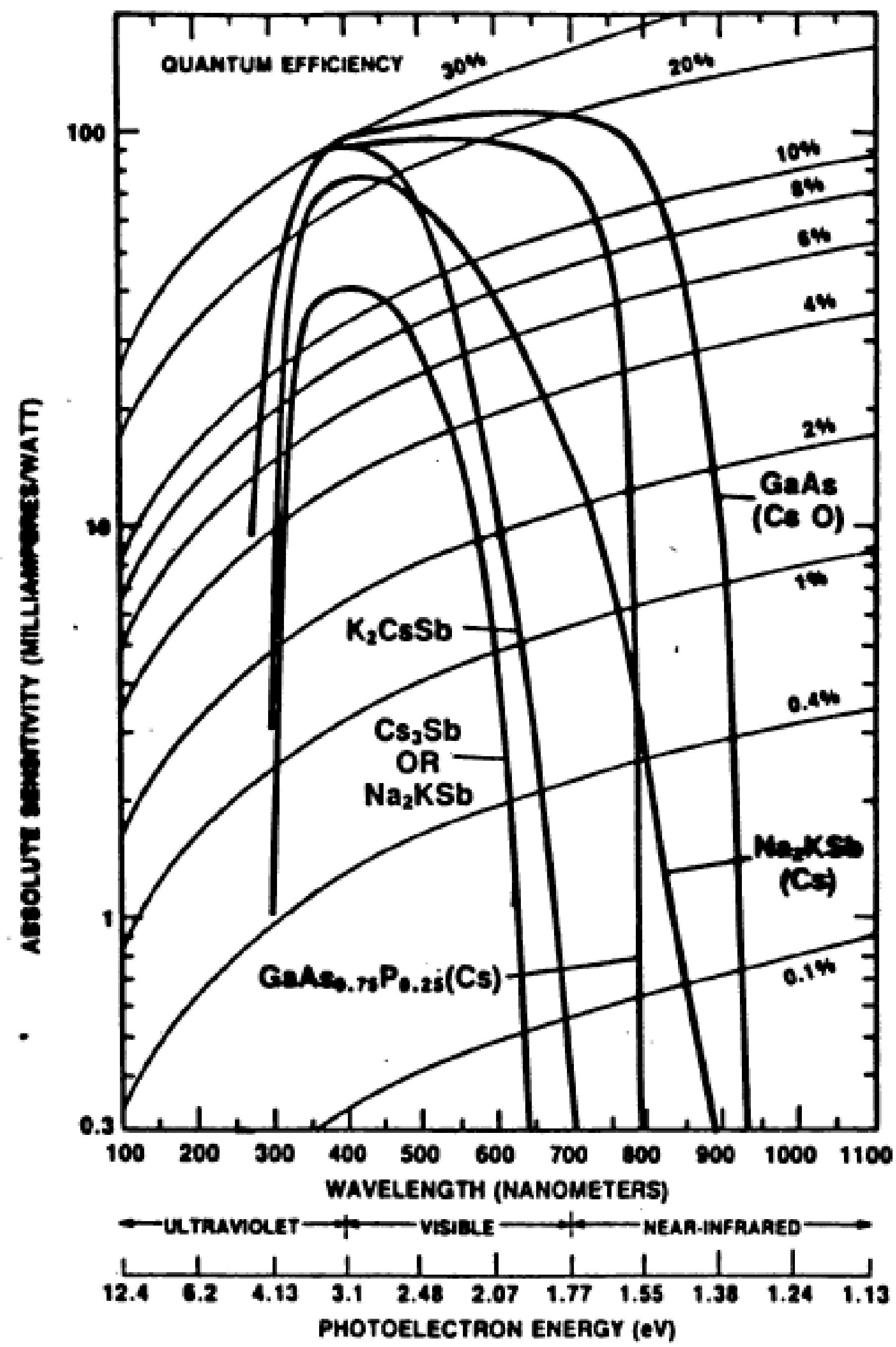
Photocathode And Lasers for PERL

T. Srinivasan-Rao, M. Babzien, C. Foerster, B. Sheehy, J. Smedley, T. Tsang

NSLA Review
4/10/01

Comparison of Photocathode Material



Candidates for Cathode

Cs: GaAs:

Measured:

High QE, >15 % at 780 nm

P*QE= 31.6 @ 780 nm

Electron temperature corresponds to ~35 meV for λ of 780 nm

1A-hr current delivered

Projected:

For 15% QE, Laser power required = 2W at cathode

Life time 10^5 C/cm^2

For a cathode spot size of 1 mm radius and 200 mA current, cathode life time is 5 hours

Improvements:

Vacuum better than $1*10^{-12}$ Torr

Reduction in field emission

Has been tested in DC Gun, Not in RF: Suitable DC GUN

K_2CsSb:

Measured:

High QE, 10-12% at 527 nm

P*QE% = 46.6 @ 527 nm

25% duty factor

32 mA average current

433 MHz RF operation

Life time few hrs. at 10^{-9} torr

Projected:

100% duty factor

200 mA current

For a QE of 10%, % W on cathode

Improvements:

Vacuum better than 10^{-9} torr

Protective coating

Heating the cathode to reduce water vapor on it

Research:

Deposition technique

High current performance

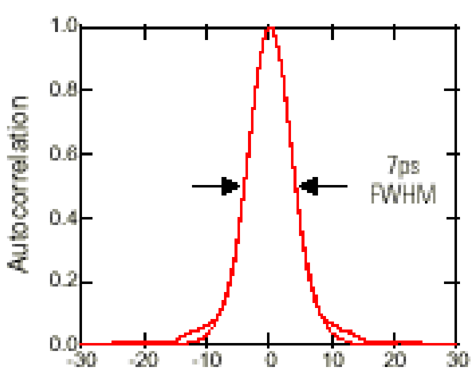
Improving life time

Integrating with gun

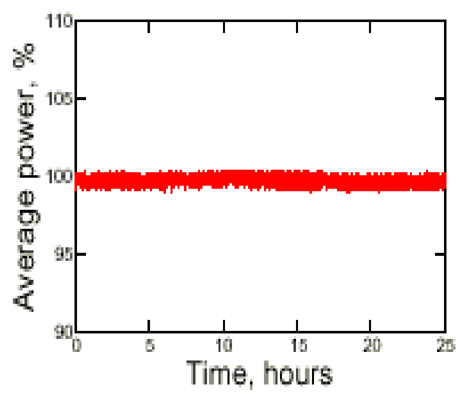
Commercial Laser

CHEETAH-X Specifications

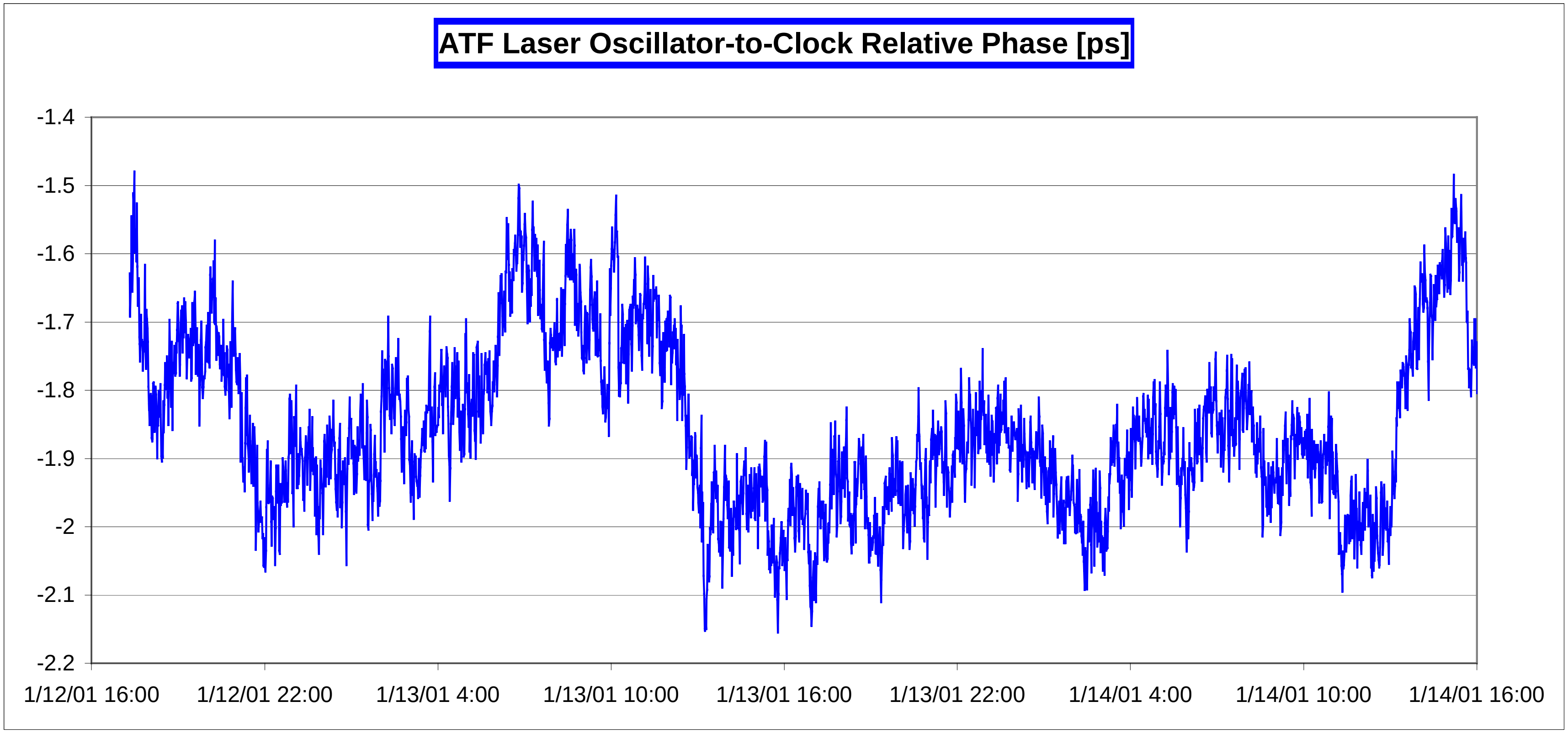
Specifications Model ▸	Cheetah-X	Cheetah-X-SHG	Cheetah-X-THG	Cheetah-X-FHG
Output Beam				
Wavelength	1064 nm	532 nm	355 nm	266 nm
Average power, minimum	>11 W	>4 W	> 700mW	> 150mW
Repetition rate - xxx	75 - 220 MHz			
Free-running frequency drift, typical (1)	10 kHz/hour			
Spatial mode	TEM_{00}, $M^2 < 1.2$			
Pulsewidth	< 7 ps	< 6 ps	< 6 ps	< 5 ps
Amplitude noise	<1% rms	<2% rms	<2% rms	<2% rms
Polarization, linear horizontal	>100:1			
Beam divergence (full angle)	<1.6 mrad			
Turn-on time				
from cold-start	<30 minutes			
from standby	<15 minutes			
Input & Ambient Requirements				
Power supply Voltage	85 to 264 VAC			
Frequency	50 to 60 Hz			
Input power, maximum	300 W			
Operating ambient temperature	15 to 35 °C			
Storage temperature	0 to 50 °C			
Relative humidity, non-condensing	≤ 80%			
Cable length, head to supply	2 meters			
Size and Weight				
Laser head, W x H x L, mass	17.0cm x 7.cm x 38.0cm, 8.0kg, (IR version only) 17.0cm x 7.8cm x 50cm, 10.0kg, (including nonlinear conversion)			



Typical autocorrelation of the Cheetah-X.



Average power variation measured over a duration of 24 hours.



- CW phasemeter (DC-10 Hz bandwidth) shown over 48 hours

Time-Bandwidth Products, Inc. Nd:YVO_4 Oscillator

- Improved stability in both energy, phase, and pointing
- High reliability reduces maintenance - realignment should be unnecessary
- Old oscillator provides emergency backup in case of failure

	LWE-131	GE-100
Pulse duration (FWHM)	20 ps	7 ps
CW power	~65 mW (currently)	500 mW
Amplitude stability	<0.3% (10kHZ-10 mHz)	<0.2%
Pointing stability	< 50 microradian	<10 microradian
Phase stability	<1 ps p-p (minutes) < 1ps/hour drift	<0.3 ps p-p (minutes) < 0.5ps/hour drift
Estimated laserdiode lifetime	> 30,000 hours*	>10,000

*-has operated 36,000 hours

Demonstrated ATF Laser Performance

Energy (dual pulse mode)	
UV on cathode	0-50 μJ
IR at CO_2 table	7 mJ
Laser output: total IR	30 mJ
IR into 2ω	5 mJ / pulse
Green	1 mJ / pulse
UV	200 μJ
Repetition rate	1.5, 3 Hz
Pulse duration (FWHM):	
Oscillator IR	7 ps
Amplified IR	14 ps
Green	10 ps
UV	8 ps
Beam ∅ on cathode (FWHM)	0.2 - 3 mm
Top-Hat Beam Profile Modulation (P-P)	<20%
Shot-to-shot stability (rms):	
Timing	<0.2 ps
Energy	≤2 %
Pointing (fraction of beam ∅)	<0.3%
Drift (8 hour P-P)	
Timing	<1ps
Energy	<15 %
Pointing (fraction of beam ∅)	<1%

Laser Research

System Integration:

- **Beam transport**

Pulse train:

- **Variable repetition rate in multiple of fundamental**

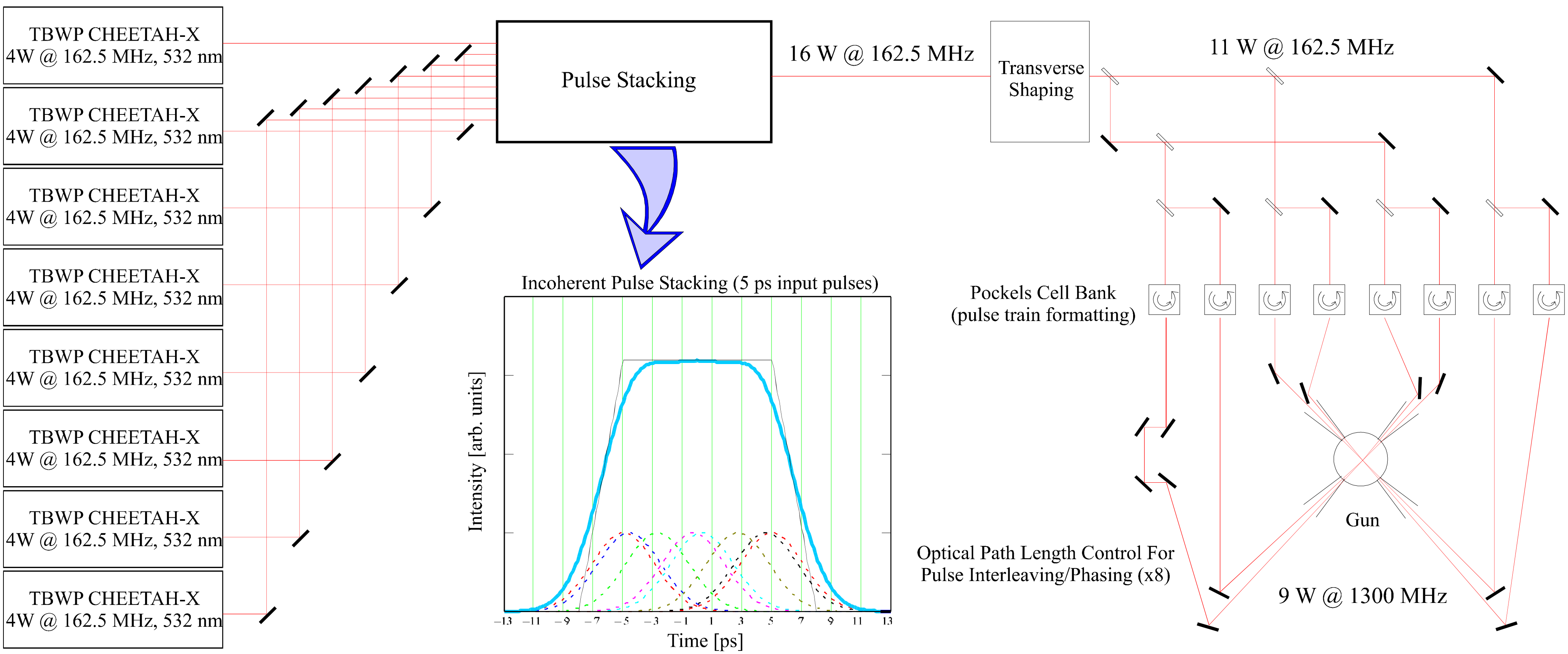
Beam Shaping:

- **Longitudinal:**
  - **Stacking**
  - **Stretching/Frequency modulation**
- **Transverse:**

Beam monitoring:

- **Pulse duration**
- **Spatial profile**
- **Amplitude stability**
- **Timing Stability**
- **Pointing Stability**
- **Feedback system**

Proposed PERL Drive Laser Block Diagram



Preliminary Beam Parameters of PERL Injector with DC Gun

F.Zhou, I.Ben-Zvi, X.Wang

Brookhaven Accelerator Test Facility

Brookhaven National Laboratory

Upton, NY 11973, USA

April 10, 2001

NSLS PERL Review

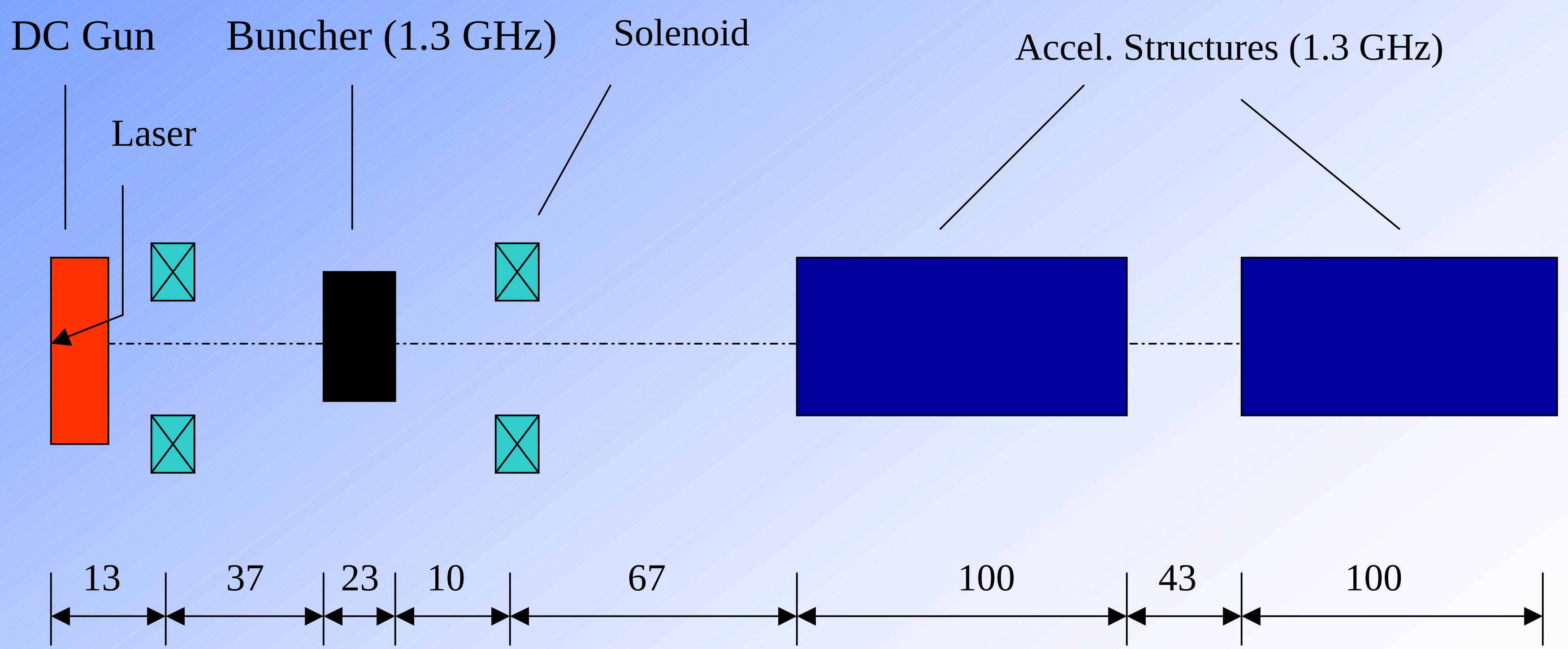
Outline

- Beam Required at the exit of PERL Injector
- Schematic Layout of PERL Injector with DC Gun
- Preliminary Simulation Results
- Summary and Outlook

Beam Requirements at the Injector Exit

- Beam Current 200 mA,i.e, 0.15 nC/bunch for L-band linac
- Energy about 25 MeV and RMS Energy Spread 25 keV
- RMS Bunch Length:3 ps or 0.9 mm
- Transverse Emittance: 1 mm.mrad @ 0.15 nC

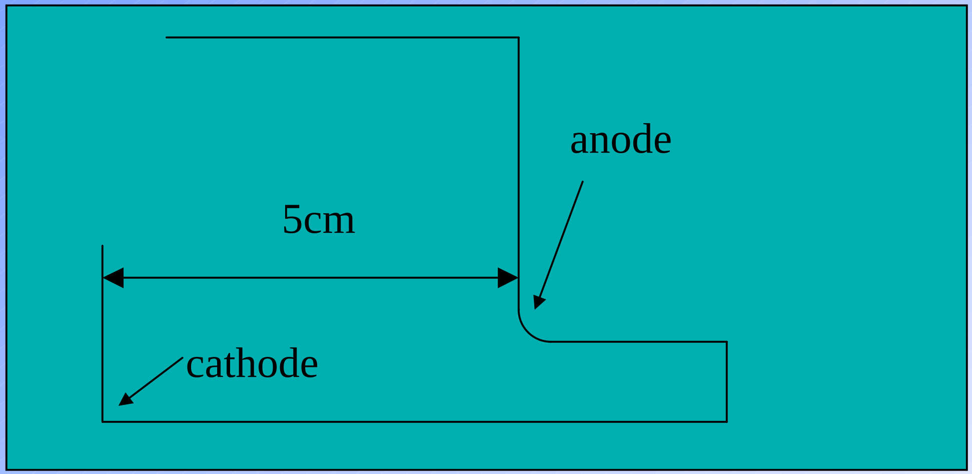
Schematic Layout of the Injector



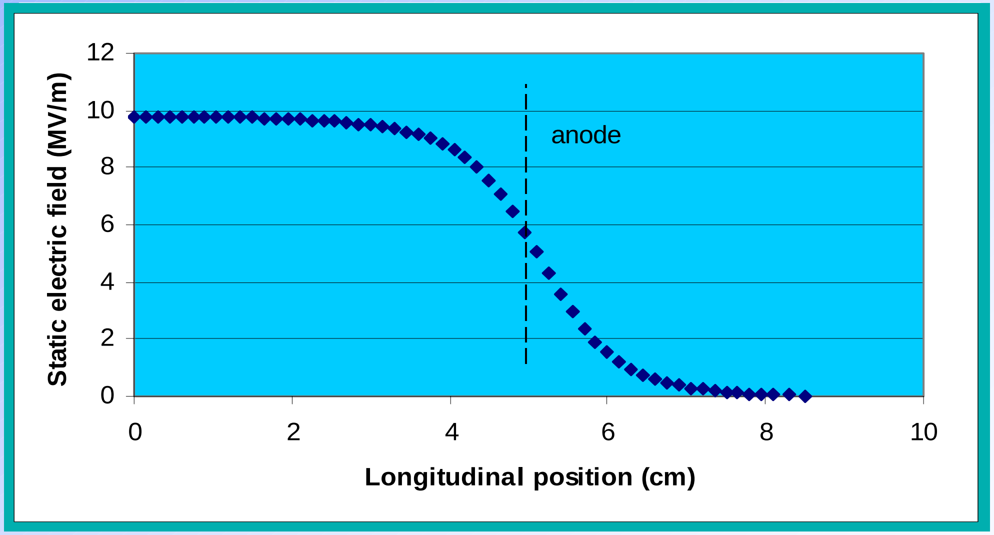
Beam Simulations

- Beam simulations starts from the cathode to the injector exit
- A package of widely used computer codes:
  POISSON (gun and solenoids),
  SUPERFISH (Buncher and accelerating structures)
  and beam dynamics simulation code:
  ASTRA (**A S**pace Charge **T**racking **A**lgoritum), which is newly developed by K.Floettmann from DESY.
- DC gun
  Schematic geometry (5 cm from the cathode to anode)
  and its electric field (500 kV)

DC Gun



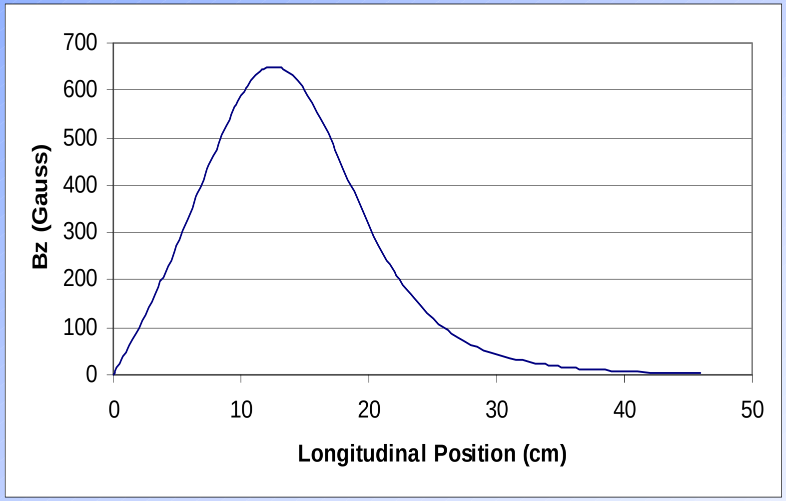
anode
5cm
cathode



Static electric field (MV/m)
12
10
8
6
4
2
0
anode
0
2
4
6
8
10
Longitudinal position (cm)

Solenoid Fields

- 1st solenoid for the emittance compensation is located at 13 cm from the cathode (just after the gun). Maximum Bz is 520 Gauss.



- 2nd solenoid (maximum Bz: 550 Gauss) is located after buncher, which has two functions:

  * further emittance compensation, since the energy is still lower, 2.0 MeV

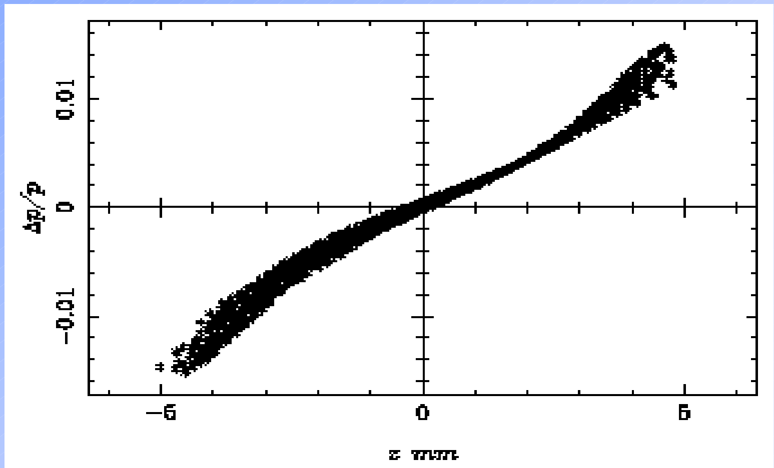
  * optics matching to the accelerating structures

Buncher

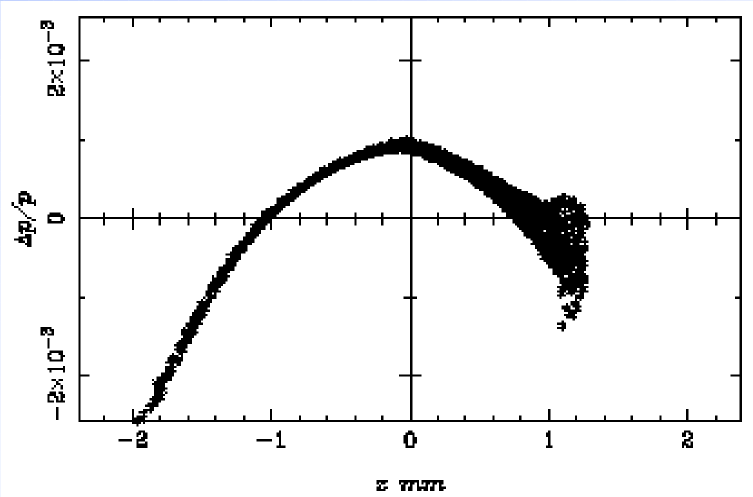
- Buncher is two-cell standing wave structures (1.3 GHz, 7.5 MV/m), which has two functions:

  * bunching the bunch from RMS length 10 ps to 3.0 ps (3mm to 0.9 mm)

  * accelerating the bunch in order to reduce the space charge effect. The RF phase is 30 degrees off-crest and its net energy gain from the buncher is about 1.4 MeV.



before the buncher

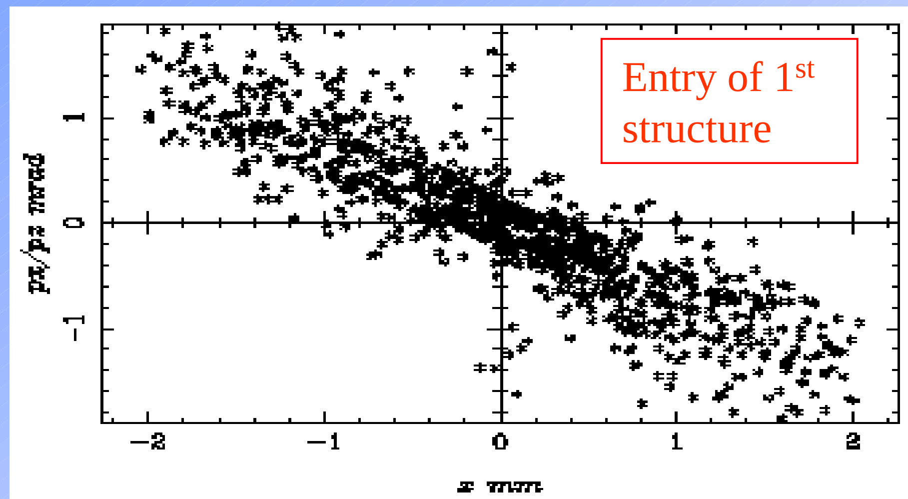


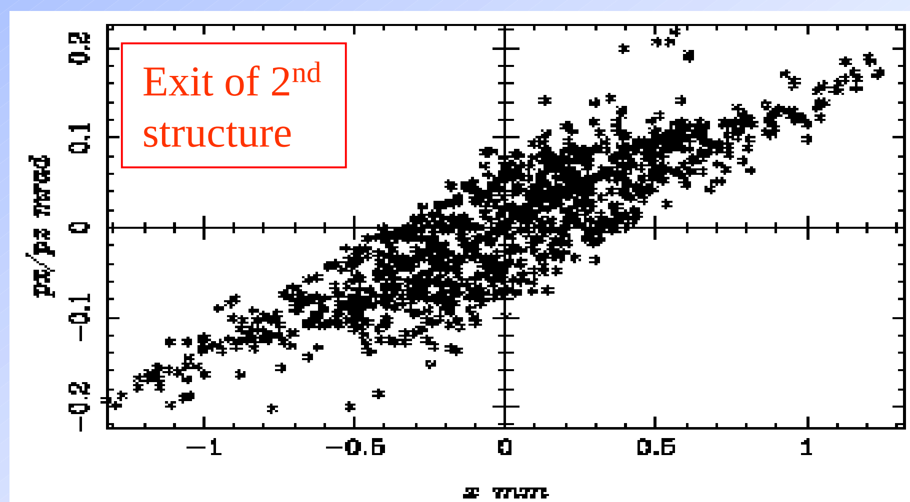
after the structures

Accelerating Structures

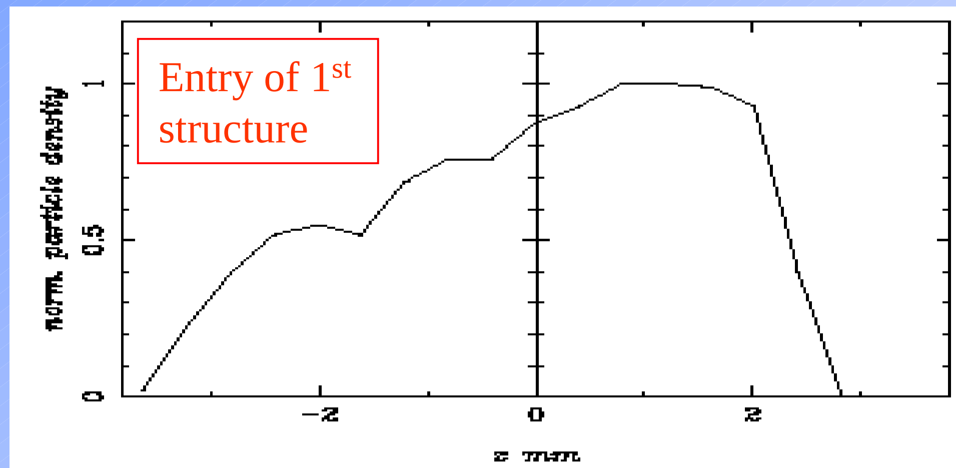
- Using the 2nd solenoid to match the beam optics to two accelerating structures. One structure (1.3 GHz) is 9-cell with 1 m, gradient is 10 MV/m. After the acceleration, the beam divergence is reduced greatly and the emittance is slightly decreased and then keeps to be constant.
- The RMS bunch length is slightly modified through two structures and then kept to 3.0 ps (0.9 mm).
- The energy spread after two structures are 25 keV at the energy of 25 MeV.

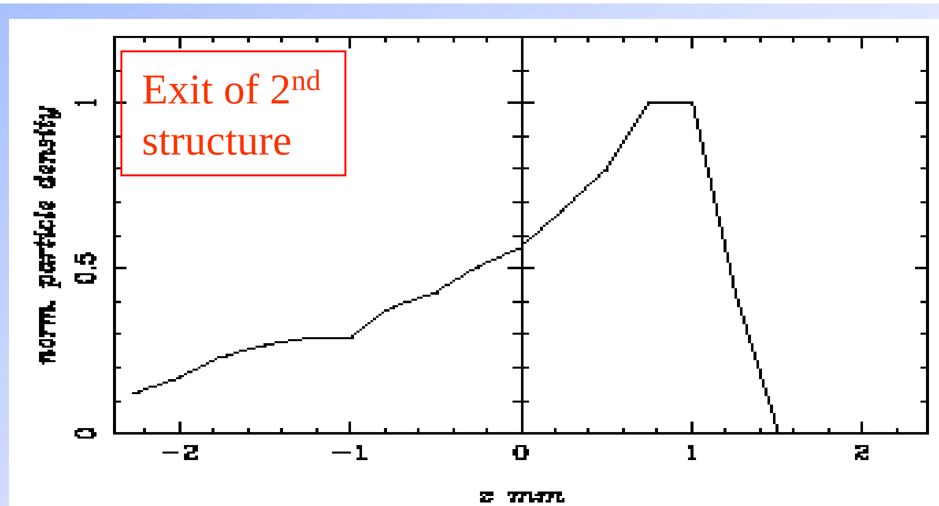
Accelerating Structures-Trans. Space



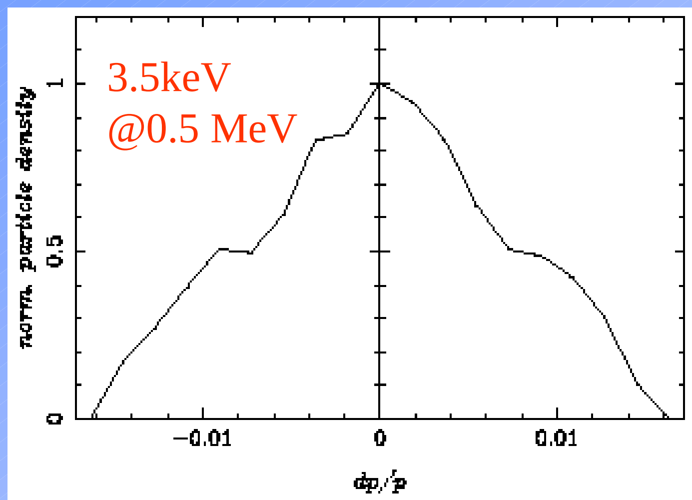


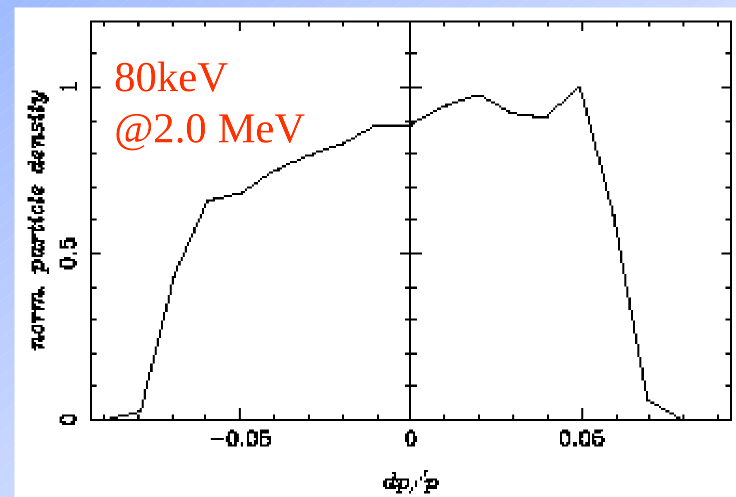
Accelerating structures-bunch length

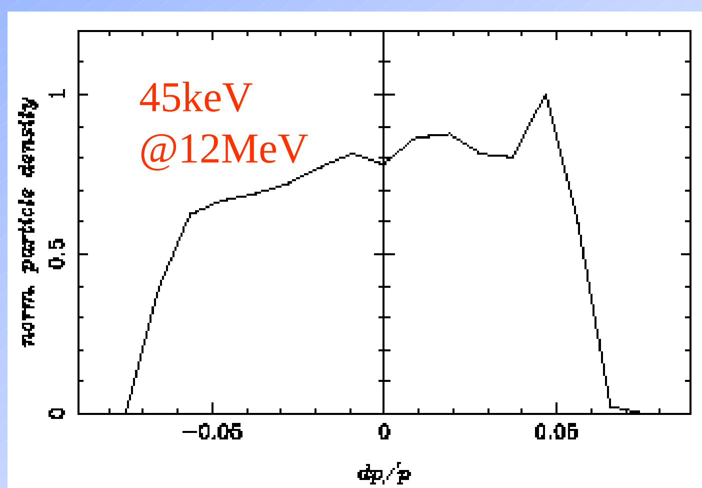


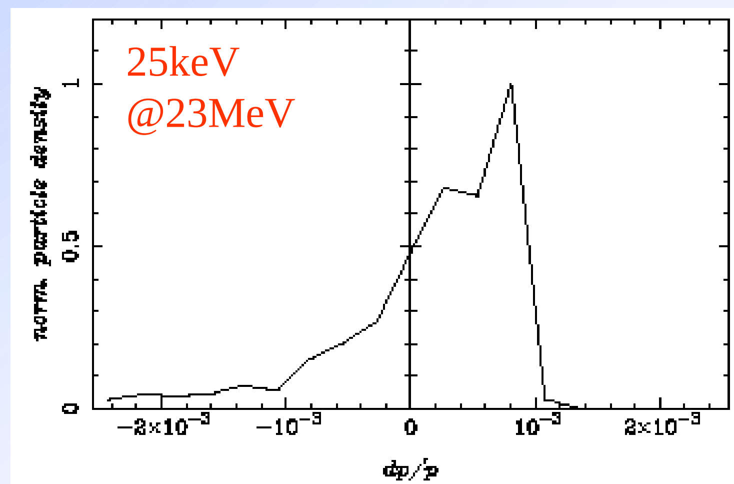


Accelerating structures-Energy spread









Simulation results

- Simulation starts from cathode. The initial distribution at the cathode :

  Longitudinal: Plateau distribution, 25 ps top, 2 ps for rise and fall time, respectively.

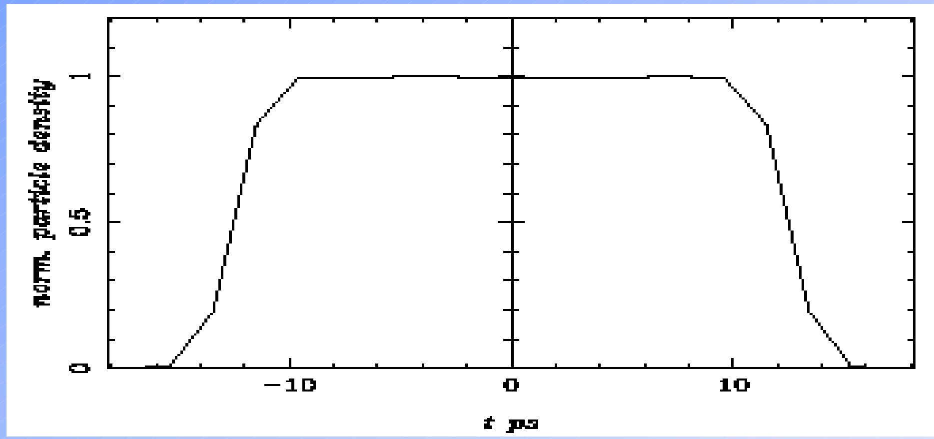
  Transverse: Uniform, RMS 1mm

  Particles: 1000

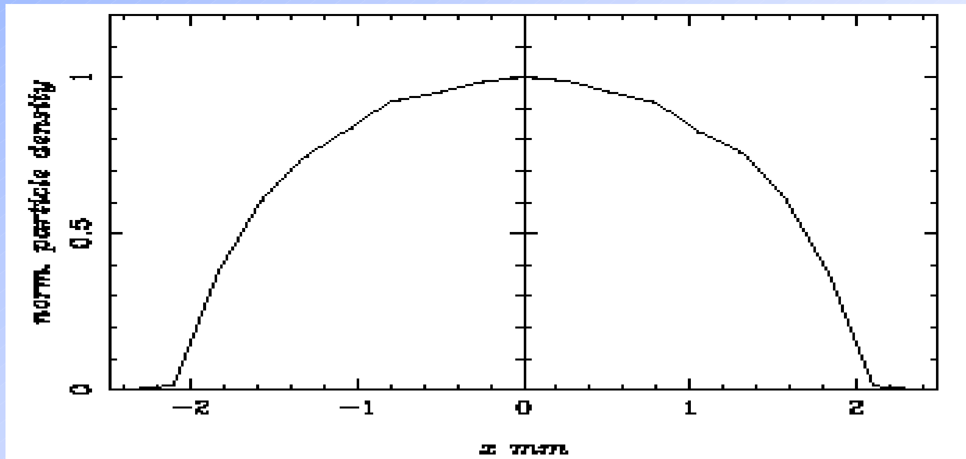
  bunch charge: 0.15 nC

- Both longitudinal and transverse emittance,beam size, bunch length, energy spread vs longitudinal position

Laser Longitudinal and Transverse Distributions on the cathode



Longitudinal

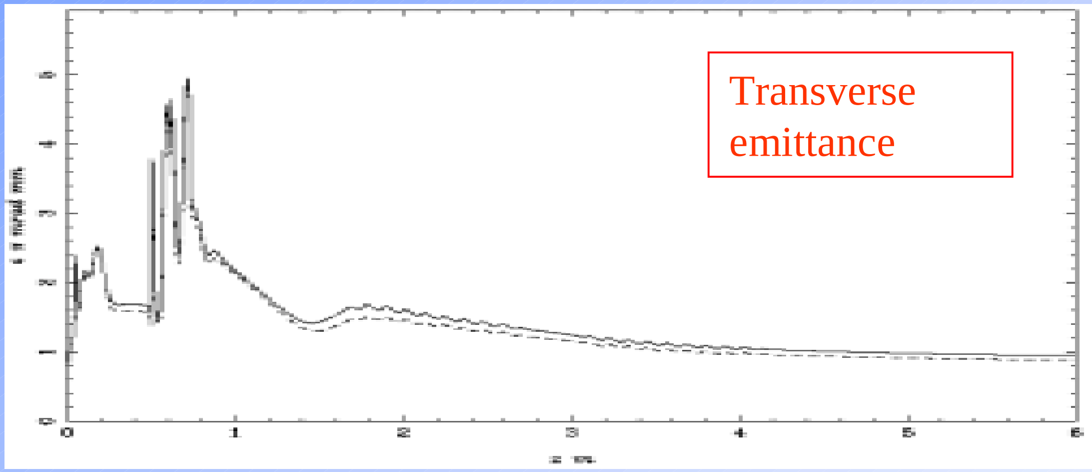


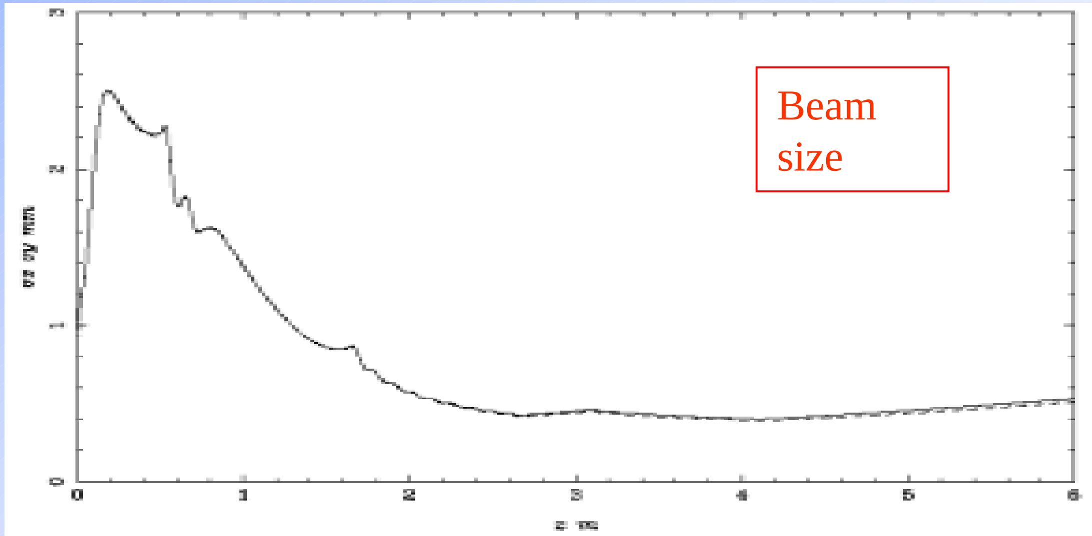
Transverse

Brookhaven Science Associates
U.S. Department of Energy

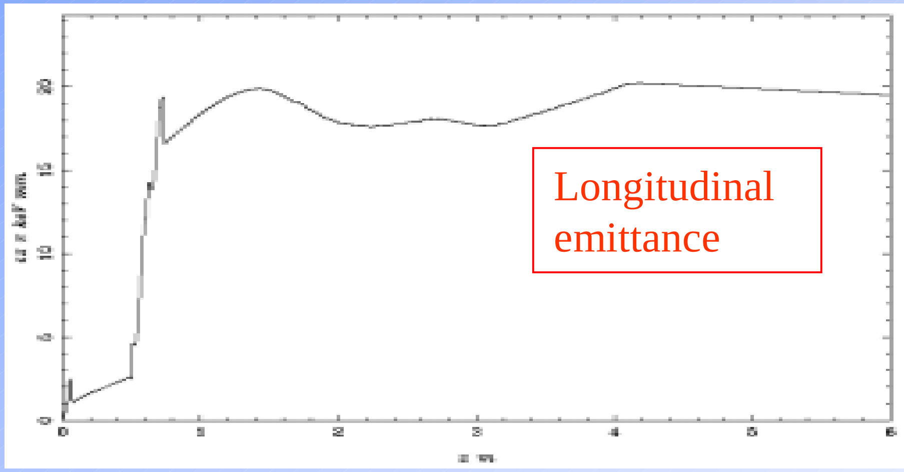
BROOKHAVEN NATIONAL LABORATORY

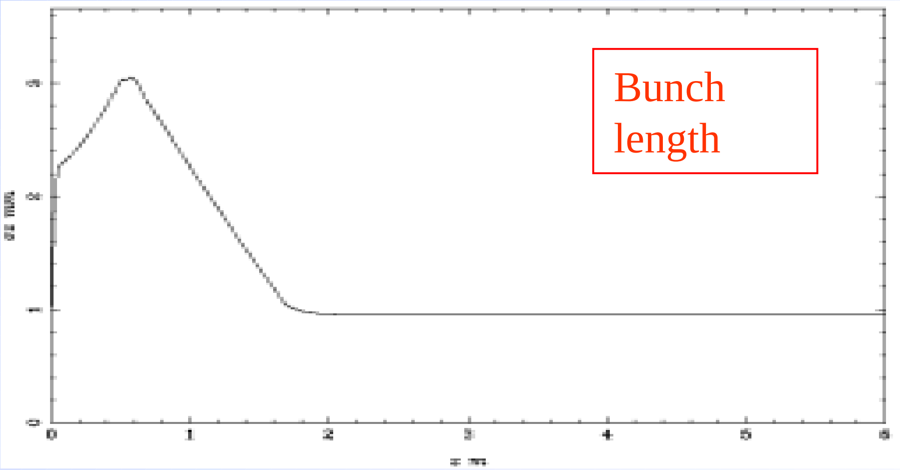
Transverse Emittance and Beam size





Longitudinal Emittance and Bunch length





Summary

	simulation	required
Energy (MeV)	23	25
RMS energy spread (keV)	27	25
RMS bunch length (ps)	3	3
Bunch charge (nC)	0.15	0.15
Longitudinal emittance (mm.keV)	20	-
Transverse emittance (mm.mrad)	0.9	1.0

The beam dynamics simulations show that the parameters of the DC gun based injector can be met with the PERL injector requirements.

A 433 MHz
Photocathode RF Gun
Ilan Ben-Zvi

Based on presentations and material of

David H. Dowell
Boeing Physical Sciences Research Center
Seattle, WA

Achievements' Summary:

- Tested at 25% duty factor (klystron limited). Typical 135 mA average current during macropulse, using 13 W Nd:YLF laser.
- 5 MeV injector (2 MeV out of gun, 3 MeV in two additional cells), 4 MW total power at peak.
- 26 MV/m on cathode
- K_2CsSb cathode QE 5% to 12%
- 10 hour lifetime at 10^{-9} torr (RF on)
- 4 μm emittance at 1 nC (severe coil misalignment, Gaussian laser)

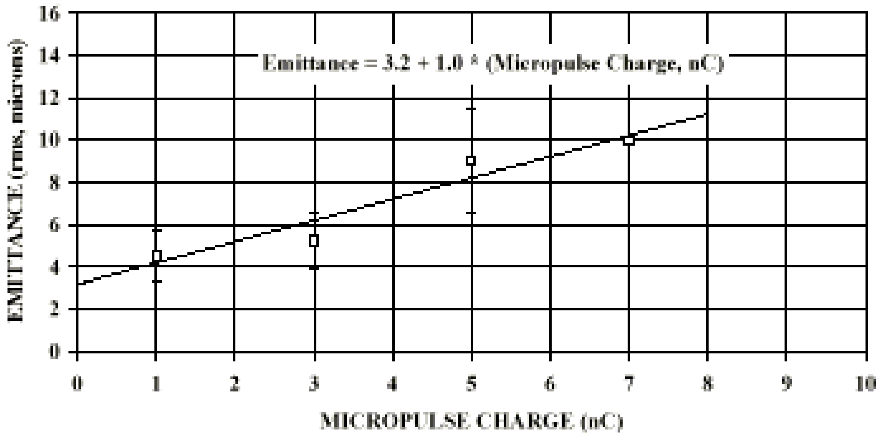
Demonstrated Performance of 433 MHz Photocathode Gun, 1992 H-D Test

Photocathode Performance:	
Photosensitive Material:	K_2CsSb Multialkali
Quantum Efficiency:	5% to 12%
Peak Current:	45 to 132 amperes
Cathode Lifetime:	1 to 10 hours
Angle of Incidence:	near normal incidence
Gun Parameters:	
Cathode Gradient:	26 MV/meter
Cavity Type:	Water-cooled copper
Number of cells:	4
RF Frequency:	433 $\times 10^6$ Hertz
Final Energy:	5 MeV(4-cells)
RF Power:	600 $\times 10^3$ Watts
Duty Factor:	25%, 30 Hertz and 8.3 ms
Laser Parameters:	
Micropulse Length:	53 ps, FWHM
Micropulse Frequency:	27 $\times 10^6$ Hertz
Macropulse Length:	10 ms
Macropulse frequency:	30 Hertz
Wavelength:	527 nm
Cathode Spot Size:	3-5 mm FWHM
Temporal and Transverse Distribution:	gaussian, gaussian
Micropulse Energy:	0,47 microjoule
Energy Stability:	1% to 5%
Pulse-to-pulse separation:	37 ns
Micropulse Frequency:	27 $\times 10^6$ Hertz
Gun Performance:	
Emittance (microns, RMS):	5 to 10 for 1 to 7 nCoulomb
Charge:	1 to 7 nCoulomb
Energy:	5 MeV
Energy Spread:	100 to 150 keV

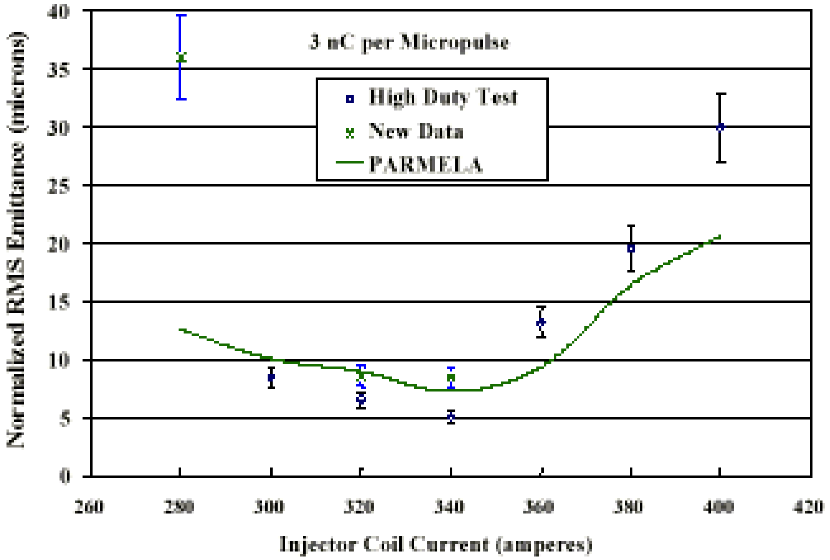
433 MHz Gun Transverse Beam Quality Measurements

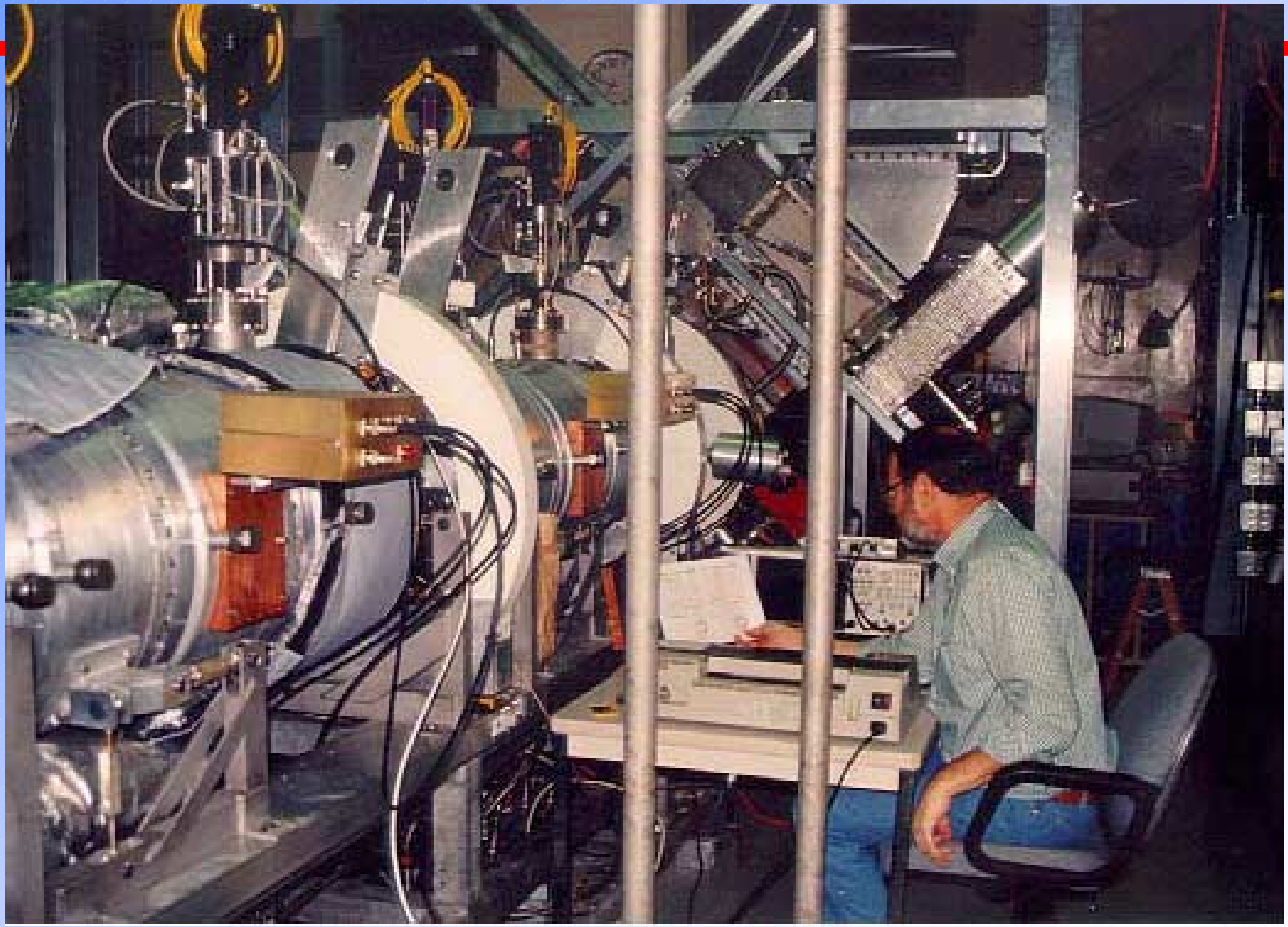
1992 and 1994-1996 Test Results

Gun Emittance Vs. Microbunch Charge



Beam Emittance at 3 nC Gaussian-Gaussian Distributions





Cooling and RF Feed for 433 MHz 5-Cell Section

3-Cell and 5-Cell APLE Cavity Booster

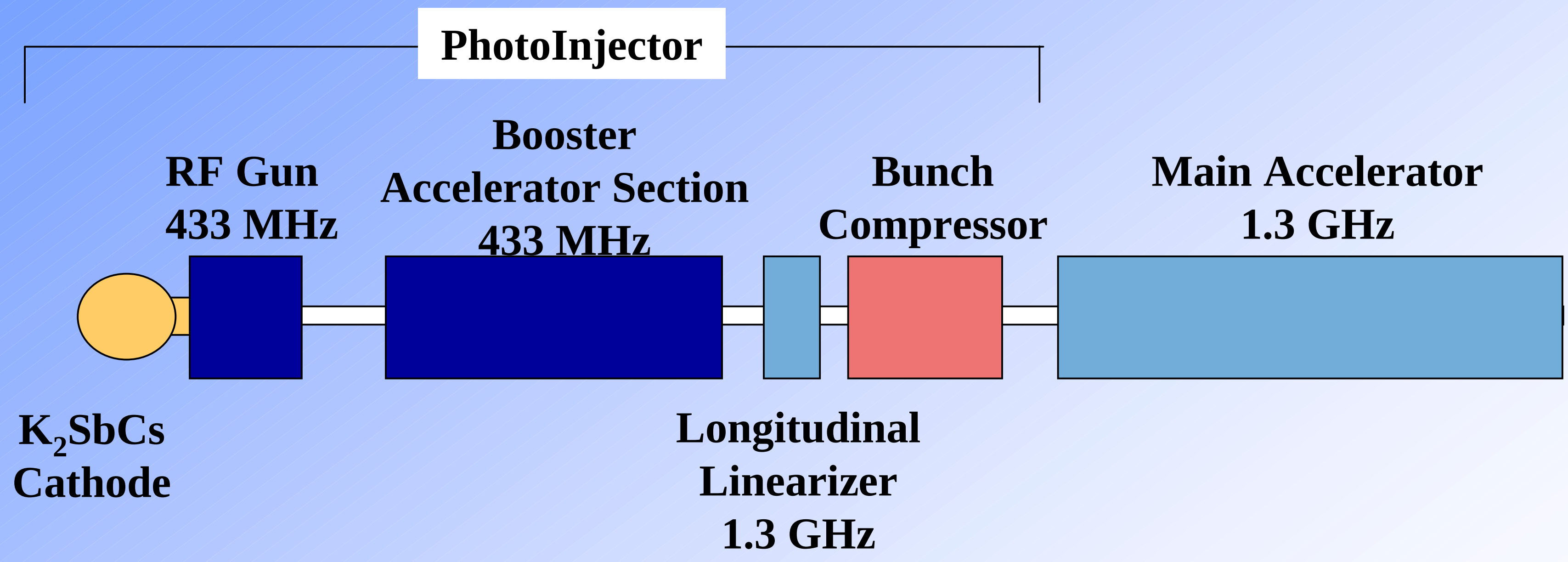
3-Cell Accelerator Cavity **5-Cell Accelerator Cavities**

1300 MHz Linearizer and Three-Dipole Chicane Compressor

1300 MHz (third harmonic) energy spectrum programming for bunch compression

Three dipole magnetic buncher and diagnostics

Layout of the 433 MHz PhotoInjector



RF Characteristics of 433 MHz Booster Cavities

RF characteristics of APLE 5-cell cavity # 2
Derived from measurements

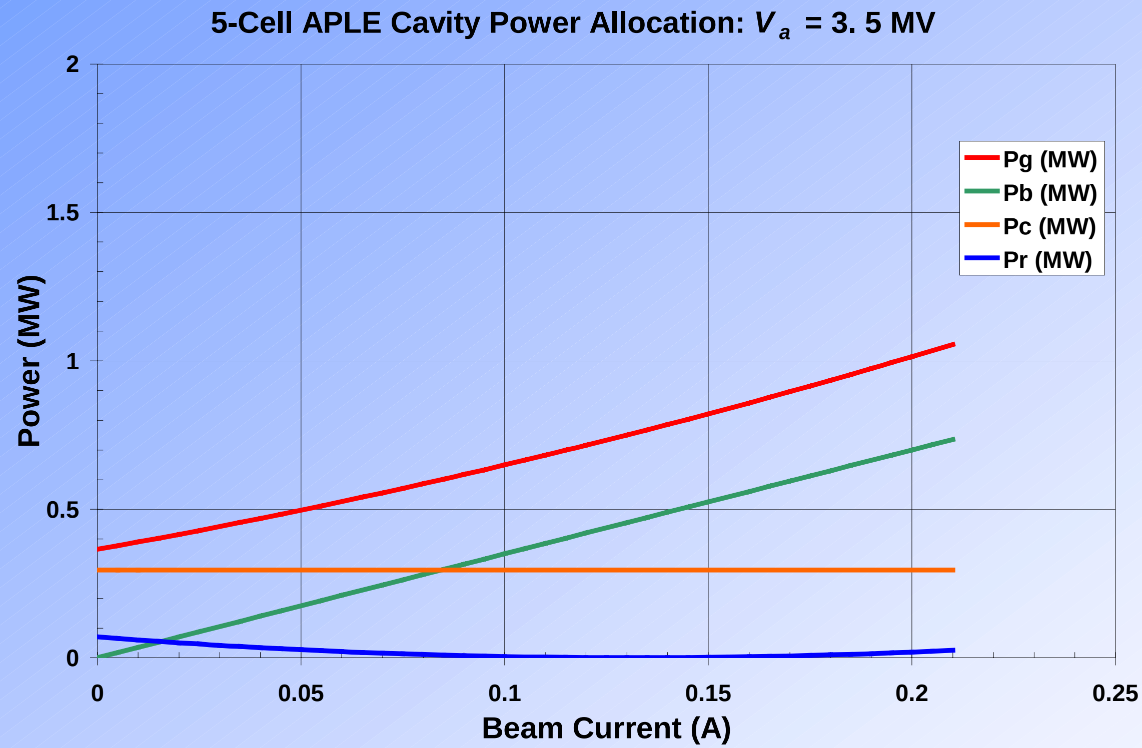
Parameter		Value	
frequency	f	433.33	MHz
shunt impedance	$R=V^2/P_c$	41.5	MΩ
coupling coefficient	β	2.56	

Operating parameters of APLE 5-cell cavity # 2
Optimized for PERL conditions.

Parameter		Value	
nominal accelerating voltage	V	3.5	MV
wall loss power	P_c	295	kW
beam power @ I_{avg}=200 mA	P_b	700	kW
forward power required	P_k	1015	kW
reflected power	P_r	20	kW

Tables provided by A.M. Vetter.

5-Cell APLE Cavity Power Allocation
Peak Energy Gain = 3.5 MV



Generator, beam, cavity loss, and reflected power as functions of beam current for 5-cell APLE cavity operation at 3.5 MV. Optimized for PERL operation.

Figure courtesy of A.M. Vetter.

RF Characteristics of 433 MHz Gun Cavities

Measured Values

Measured Gun Cavity RF Characteristics

Parameter		L1	L2	Units
frequency	f	433.33	433.33	MHz
shunt impedance	$R=V^2/P_c$	2.86	4.28	MΩ
coupling coefficient	β	3.1	3.1	

Operating Parameters for Existing Gun Cavities
External Coupling Coefficient β=3.1

Parameter		L1	L2	Units
nominal accelerating voltage	V	0.9	1.1	MV
wall loss power	P_c	285	285	kW
beam power @ I_{avg}=200 mA	P_b	180	220	kW
forward power required	P_k	515	545	kW
reflected power	P_r	50	40	kW

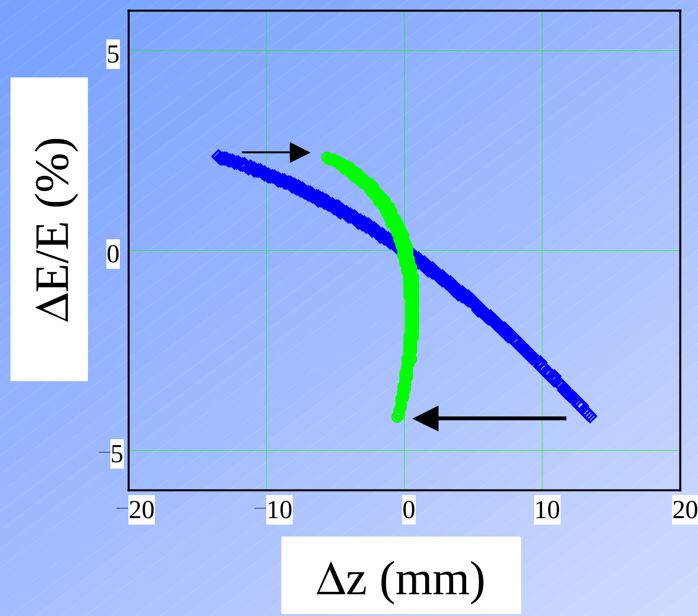
Optimized for 200 Milliamperes

Operating Parameters for PERL-Optimized Gun Cavities
External Coupling Coefficient β=2.0

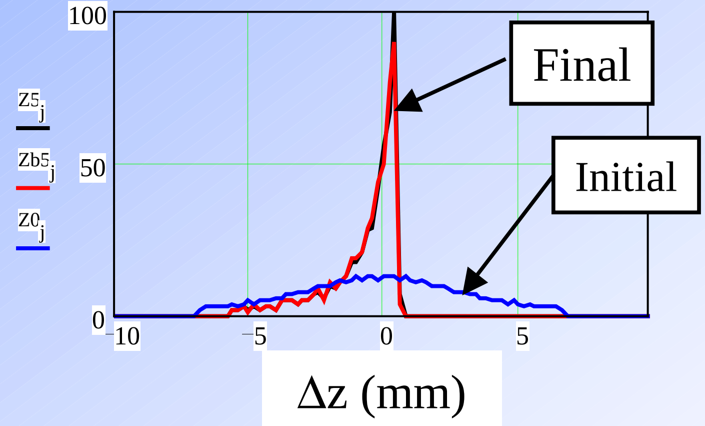
Parameter		L1	L2	Units
nominal accelerating voltage	V	0.9	1.1	MV
wall loss power	P_c	285	285	kW
beam power @ I_{avg}=200 mA	P_b	180	220	kW
forward power required	P_k	470	505	kW
reflected power	P_r	5	2	kW

Data supplied by A.M. Vetter.
See also:
J.L. Warren, T.L. Buller and A.M. Vetter, "Design of MCTD Photoinjector Cavities", Proc. 1989 IEEE PAC, Vol I, pp.420-422. May 20-27, 1989, Chicago, Illinois,

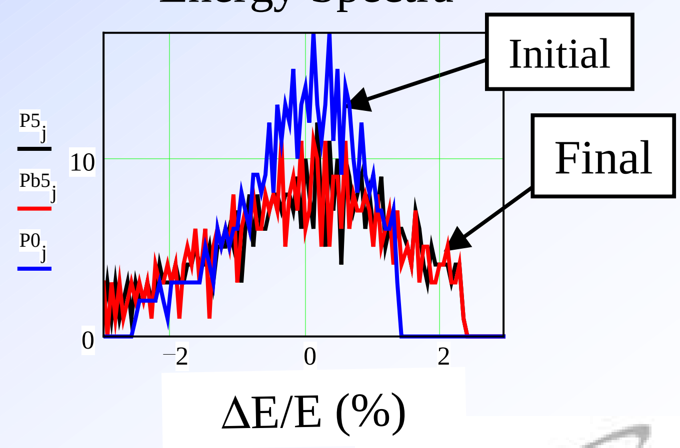
Compression With PERL Parameters, Non-Linearized Phase Space



Microbunch Shape

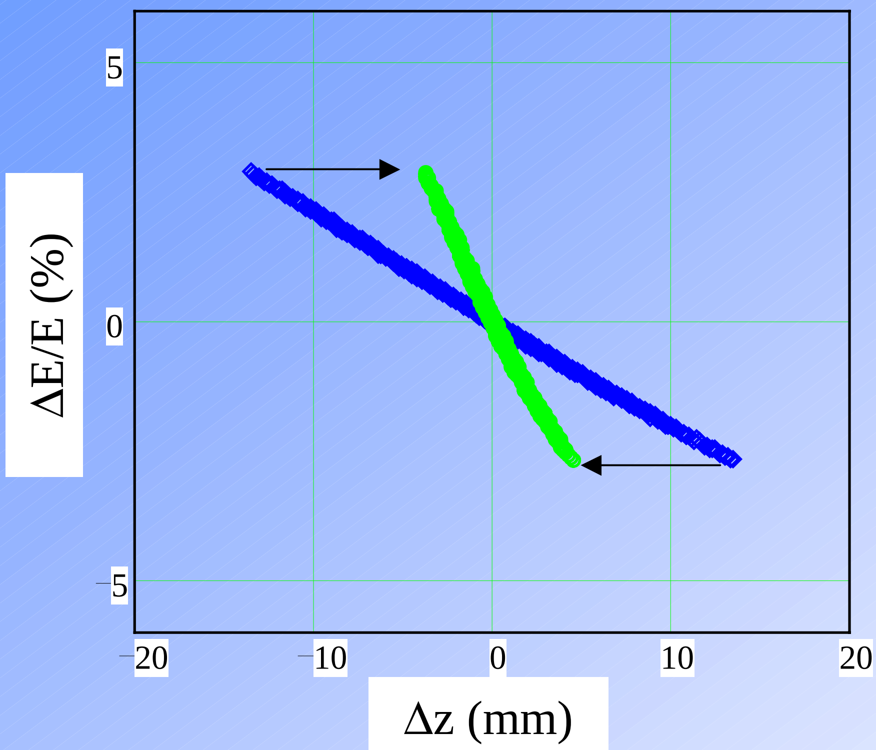


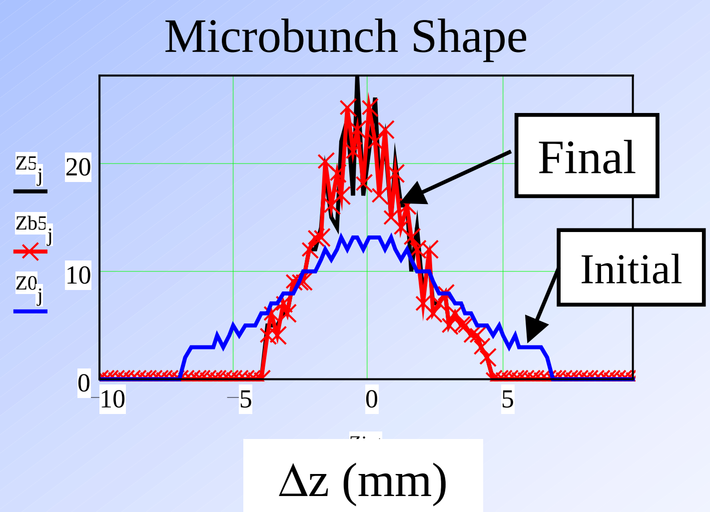
Energy Spectra

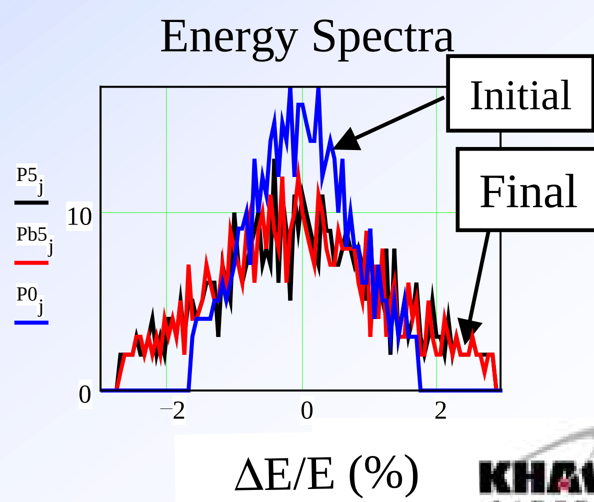


Boeing Style Compressor
10 MeV Compression
Bunch Length: 47=>10 ps
Emittance (CSR only): 1=>1.05 microns (?)
Peak Current: 10=>48 amps

Compression With PERL Parameters, Linearized Phase Space



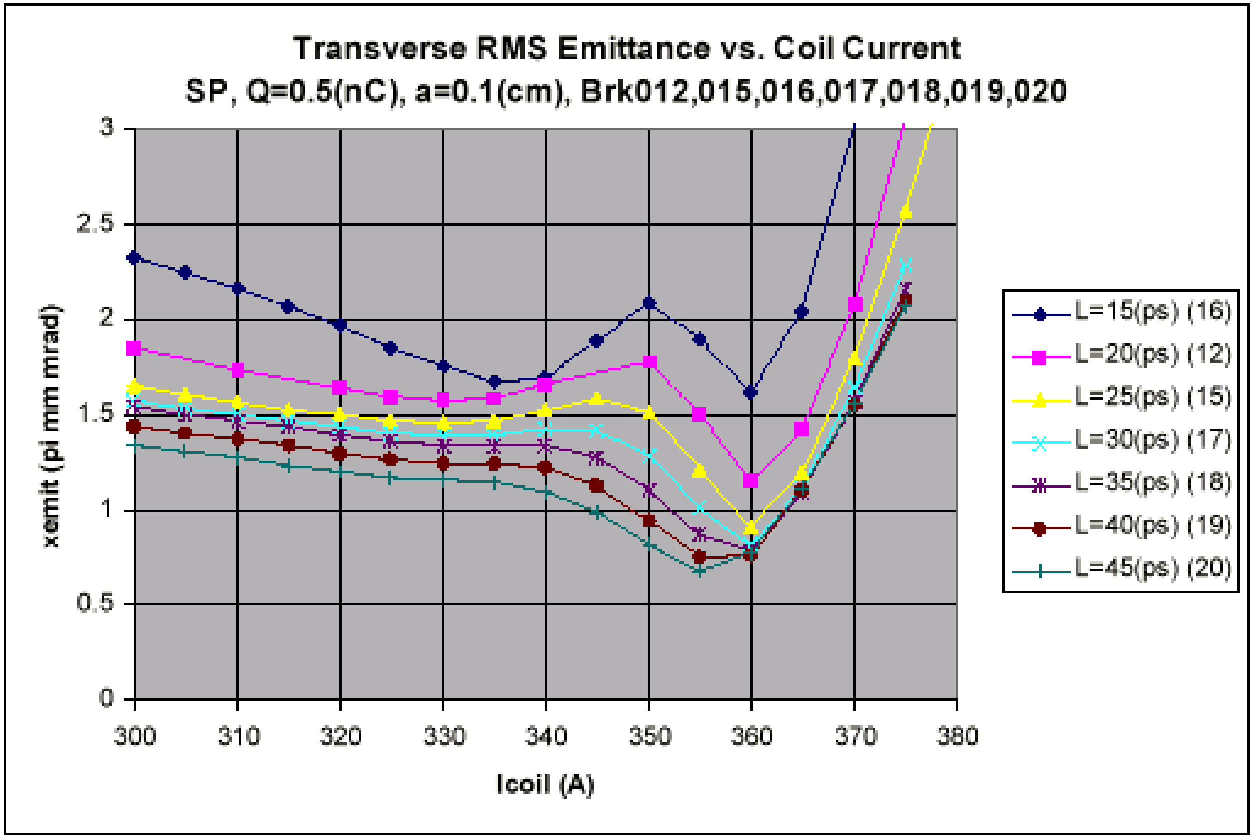




Boeing Style Compressor
10 MeV Compression
Bunch Length: 49=>15 ps
Emittance (CSR only): 1=>1.3 microns
Peak Current: 10=>34 amps

Transverse Emittance

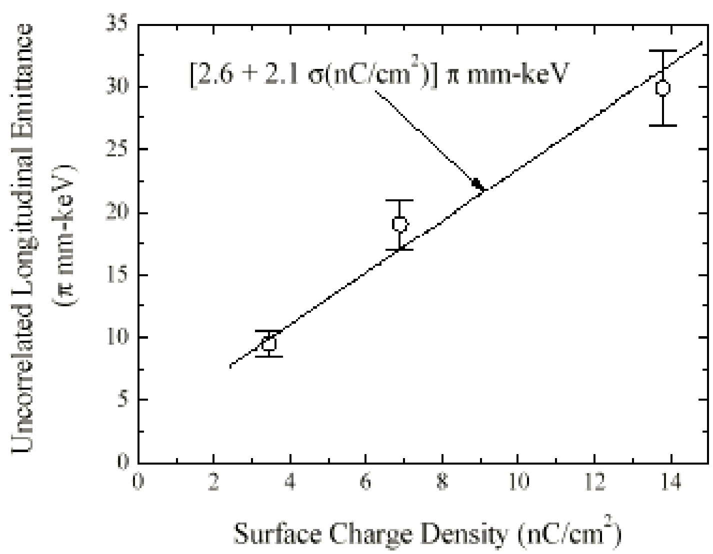
PARMELA_B Simulations at 0.5 nC



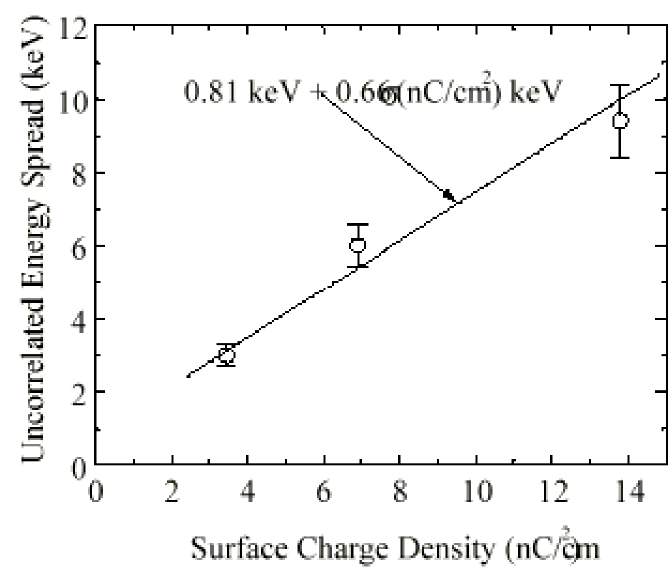
Longitudinal emittance

Compare to 90 mm-keV at beam lines

The Uncorrelated Emittance Grows Linearly with Surface Charge Densities Below the Space Charge Limit



In These Experiments Most of the Emittance Growth Was due to Increased Energy Spread



Pulse length a constant 11 ps(rms)

10 nC/cm² corresponds to 11 MV/m

Ref: D.H. Dowell et al., PAC97.

Summary and Conclusions

433 MHz-Based PhotoInjector Configuration:
Gun, Booster, Linearizer, Compressor

Non-linearity Due to RF Waveform
Requires Third-Harmonic Linearizer

433 MHz APLE Cavities Satisfy PERL Requirements

Emittances of PERL can be met

Preliminary CSR Calculations Show Some Emittance Growth
Full Start-to-End SC+Wakes Calculation Still Needed

L-band Based Photocathode injector for PERL

X.Y. Chang, X. J. Wang and I. Ben-Zvi
National Synchrotron Light Source
Brookhaven National Laboratory
Upton, NY 11973, USA
April 10, 2001
Presented at NSLS PERL Review

Outline

- Introduction
- First order simulations of L-band RF gun for PERL
- Conclusion and Summary

Introduction

- **Requirements for beam parameters:**

  PERL requires 200 mA, and 0.5 mm-mrad normalized RMS Emittance. 25Mev at linac exit. For 1300Mhz RF gun it needs 150pc per bunch.

- **Why use L-band injector?**

  A. Same as main linac frequency, simplify operation, such as cost, synchronization.

  B. Potential for higher field operation ($\propto\sqrt{f}$) which can reduce space charge effect.

Major issues in L-Band RF Gun injector.

A. Field on cathode for a 1.6 cell RF gun:

Field gradient	45 C°	LN_2
50Mv/m	4.5MW	1.1MW
25Mv/m	1.1MW	350KW
15Mv/m	350KW	110KW

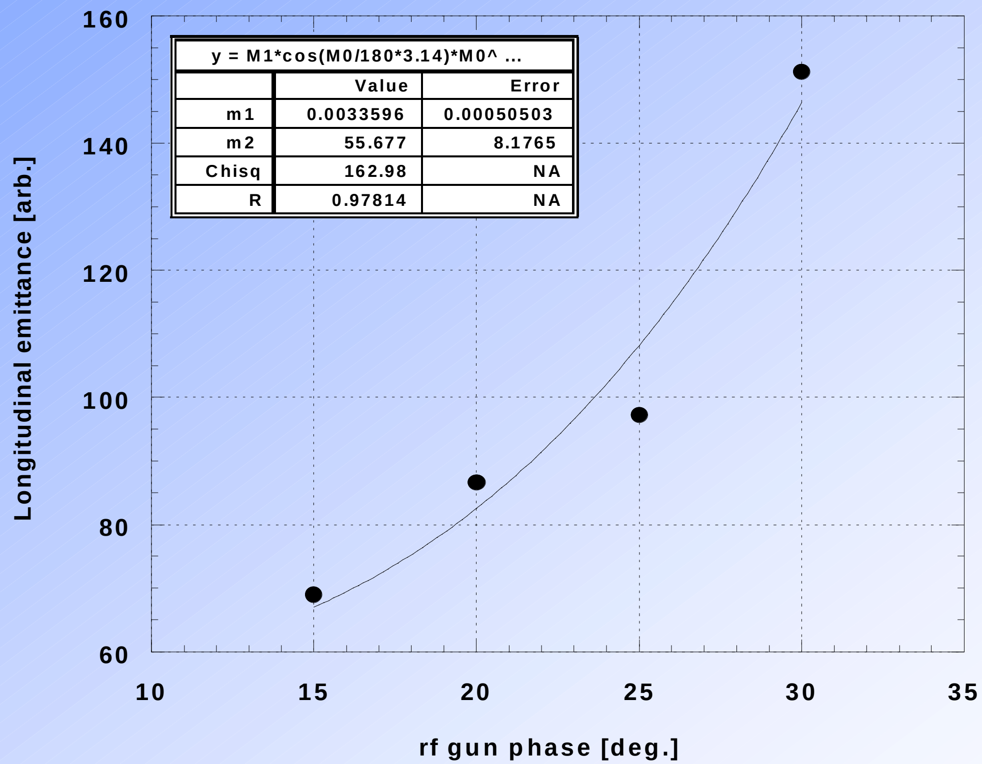
A LN_2 cooling method is proposed to improve Q and vacuum, therefore, reduce required power and extend cathode lifetime.

B. Heat dissipation problems:

We can relieve this problem by trying using a bigger size cavity works at higher order mode.

■ Longitudinal phase space ($\propto\varphi^3$):

Our major promise is to make the volume of 6-D phase space minimum at linac exit, Not only the transverse or longitudinal emittance. ($\varepsilon_z \times \varepsilon_x^2$)



Simulation

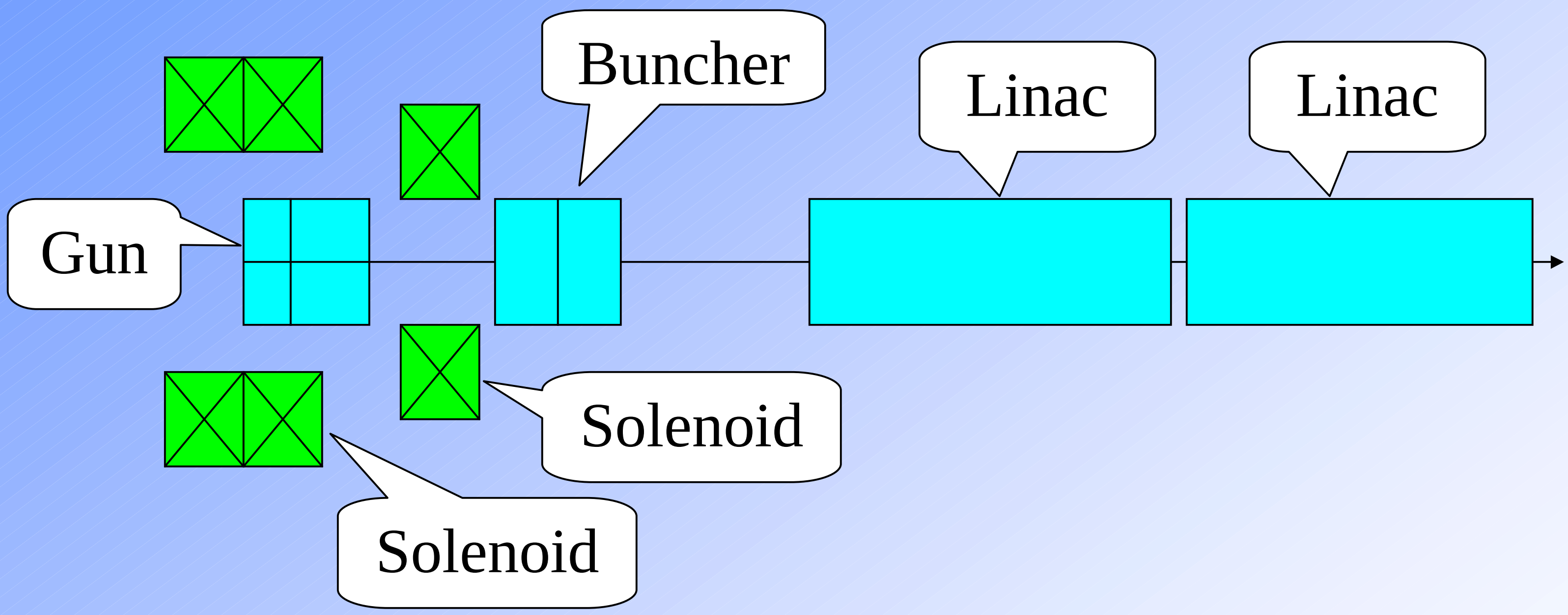
- Programs be used:

 POISSON (for solenoids).

 SUPERFISH (Gun, Buncher and accelerating structures)

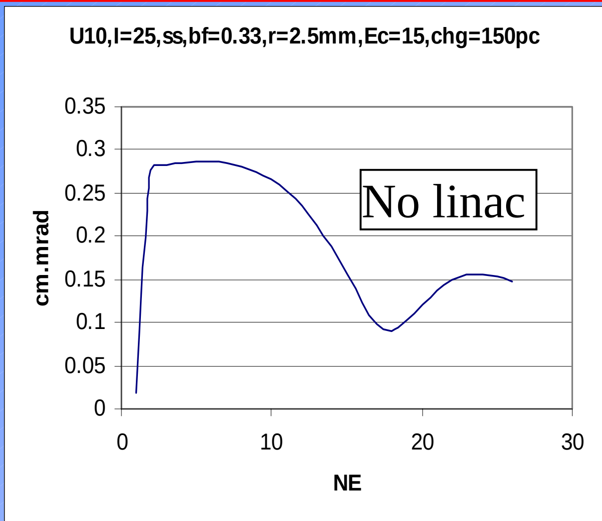
 PARMELA (for beam dynamics).

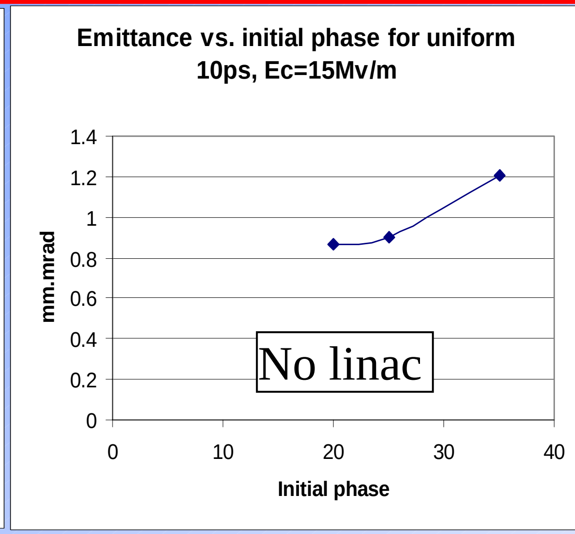
- Layout of L-band RF gun injector for PERL

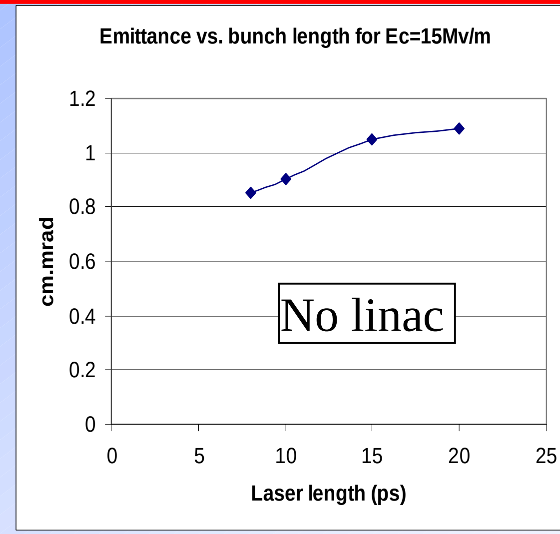


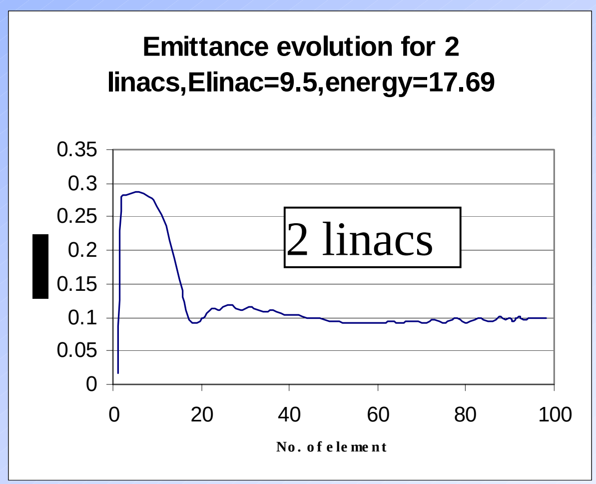
Layout of L-band RF gun injector for PERL

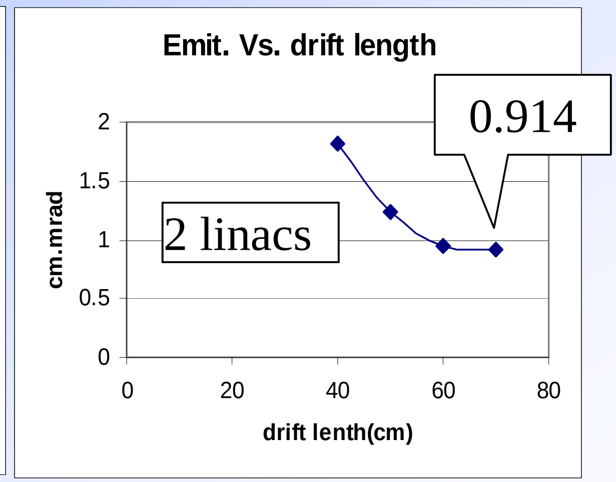
- Performance of 15Mv/m field on cathode, no linac. 1.5 gun











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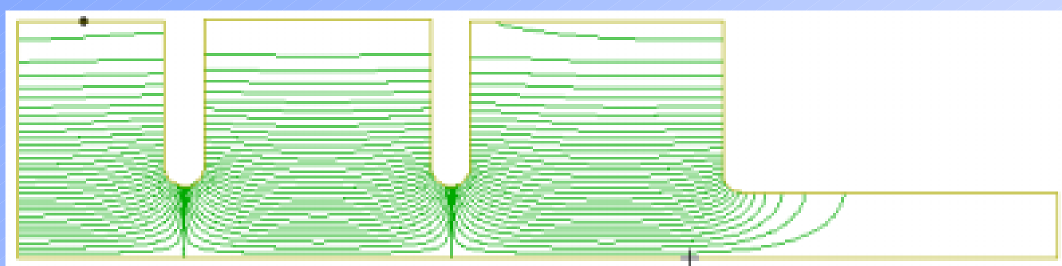
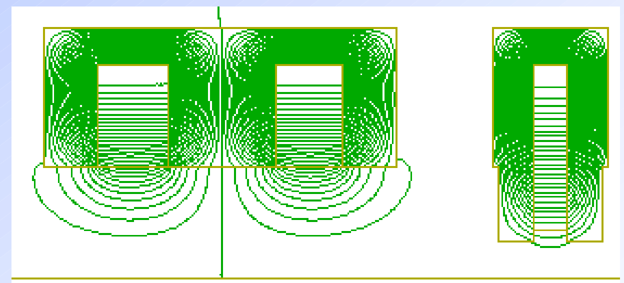
■ 2.5 cell gun.

A. Why use 2.5 cell gun ?

For 30 % increase power, to achieve higher energy at gun exit (1.4---2.35 MeV), which leads to significant reduce in space charge effect.

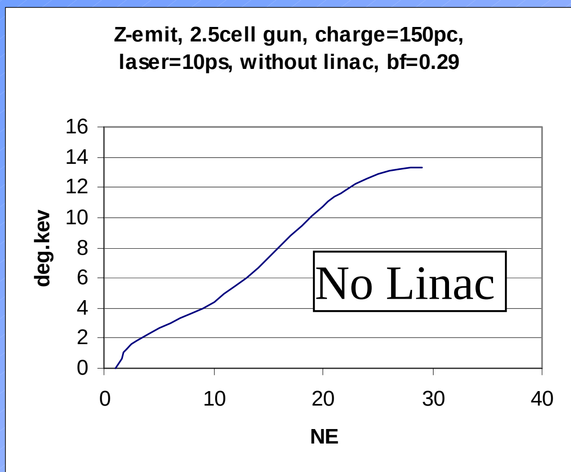


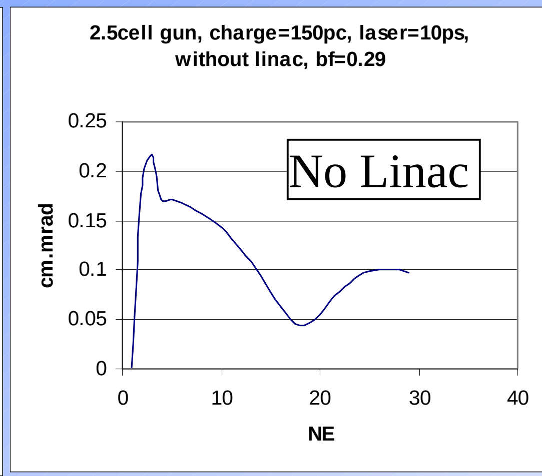


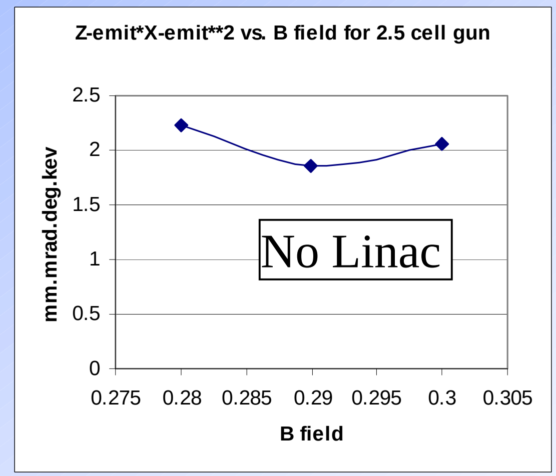
Field distribution for 2.5 cell gun

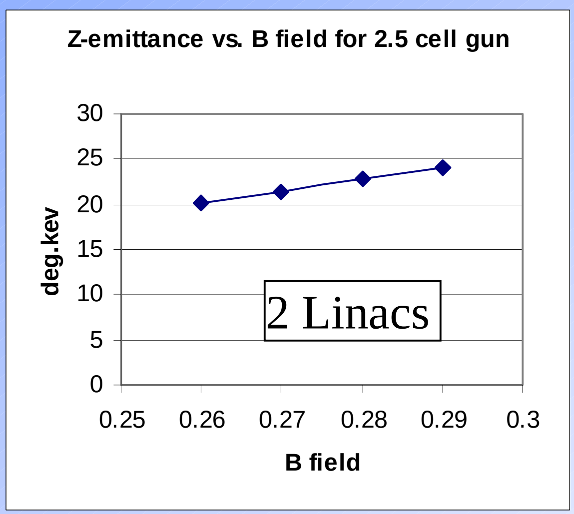
Solenoid for 2.5 gun

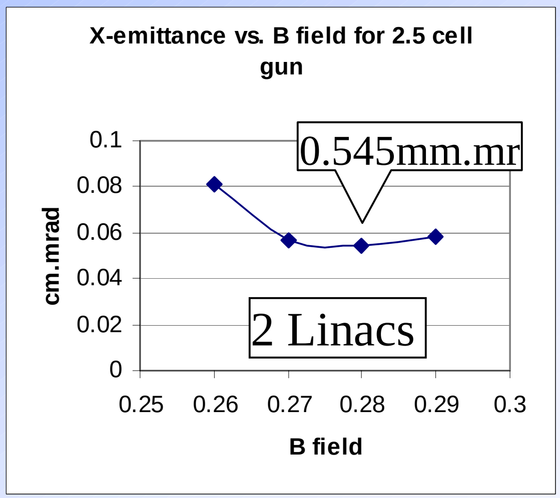
■ Performance of a 2.5 cell gun, no bunching cavity

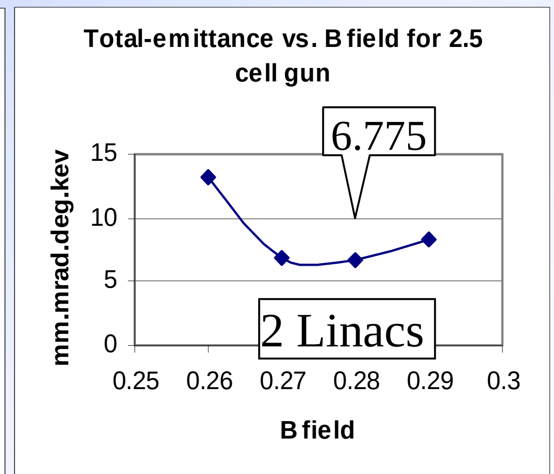












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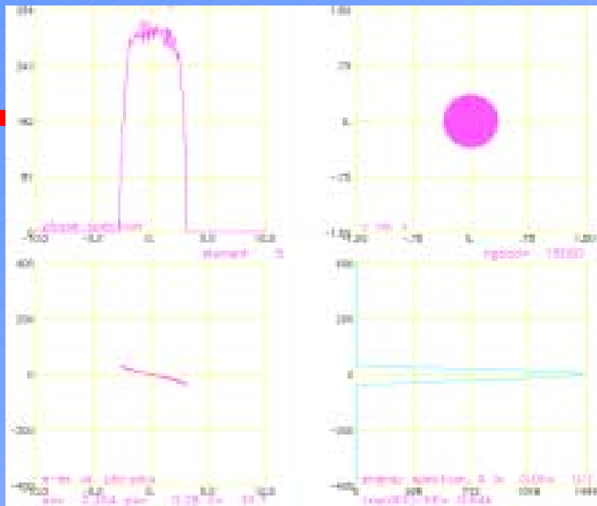
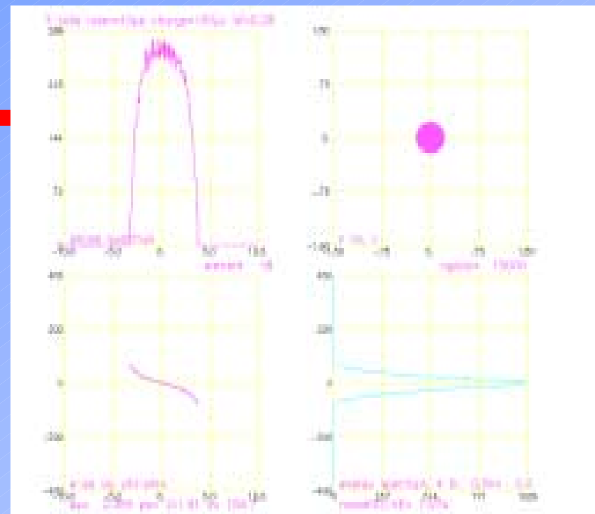
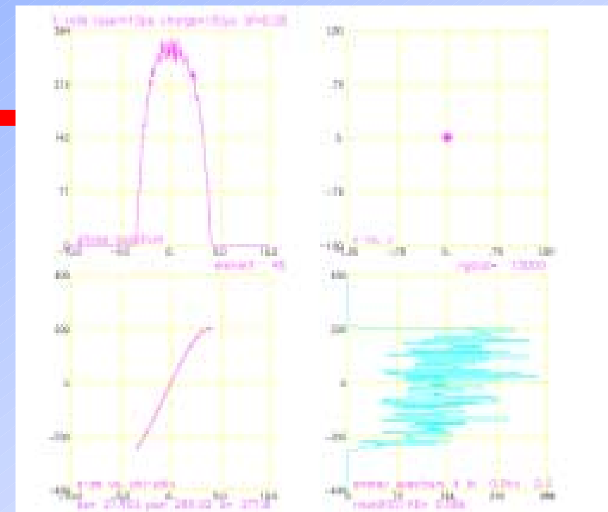
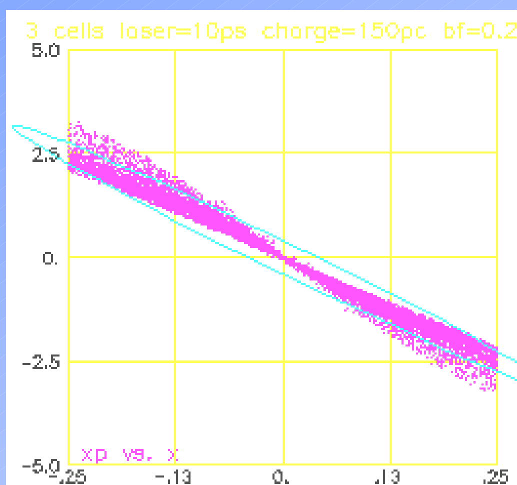
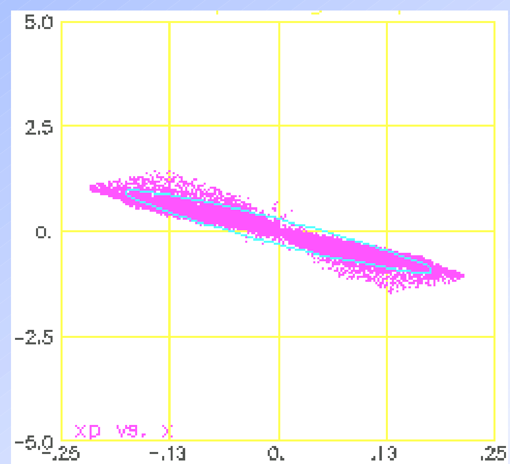








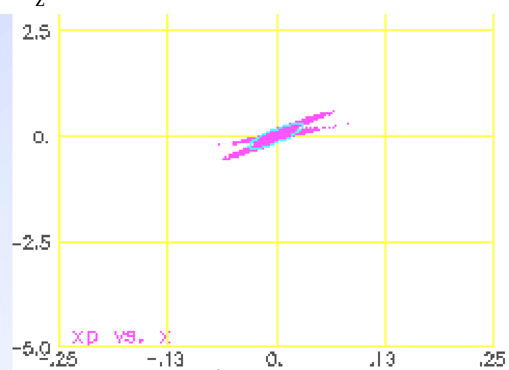
Gun exit



Linac entrance

Energy=21.9, RMS(dkE)/kE=0.58%

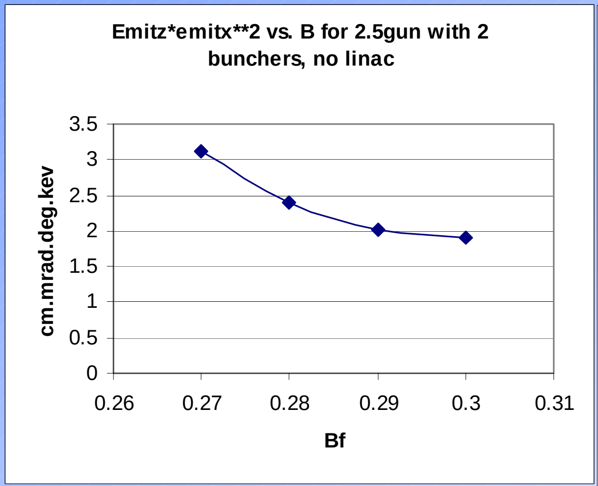
σ_z = 1.24mm



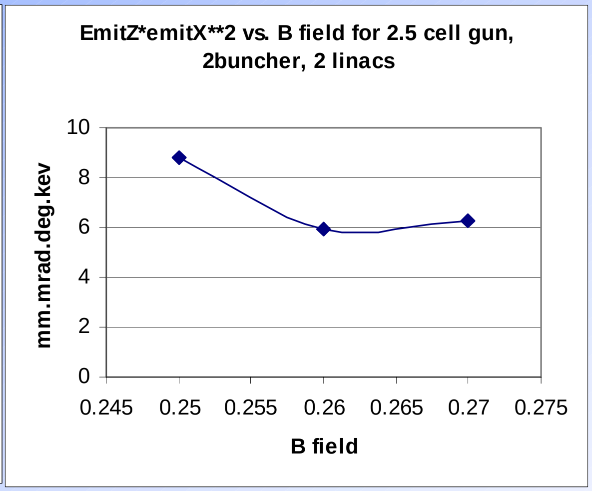
Linac exit

■ 2.5 cell with bunching cavities.

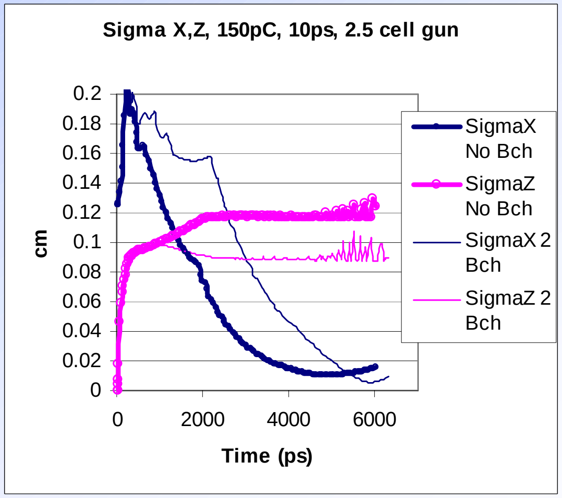
The bunching cavity is used for the purpose of bunching beam before entering linac. But by using 2.5 cell gun, beam energy is a little bit too high for bunching. In case E=2.35MeV, it needs 3% energy spread and 1m drift space to compress 1mm. So, this way may not be efficient. But it does work.



No linac



2 linacs



σ_z and σ_x

Brookhaven Science Associates
U.S. Department of Energy

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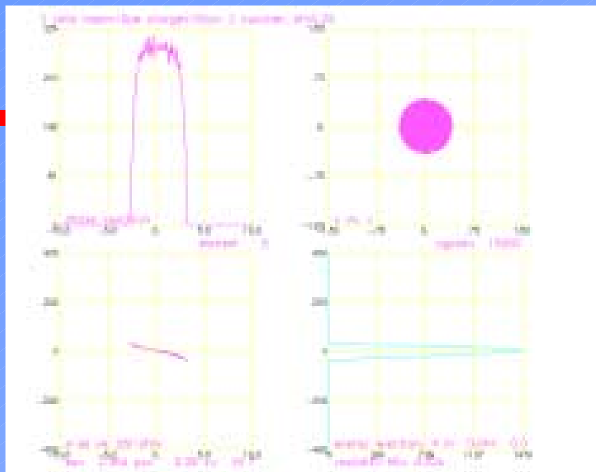
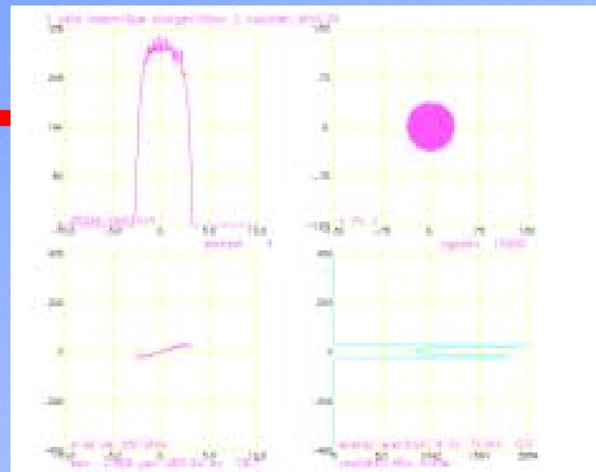
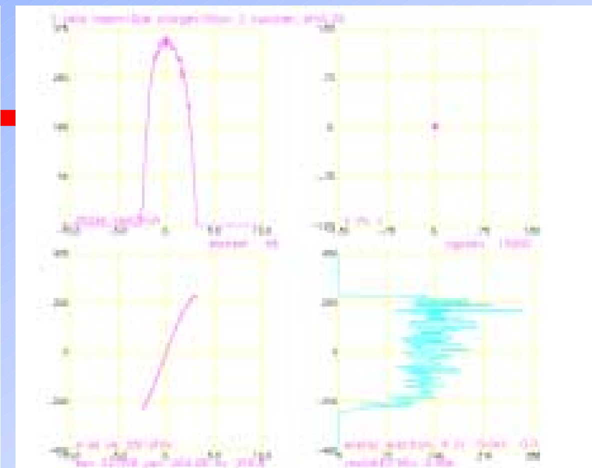


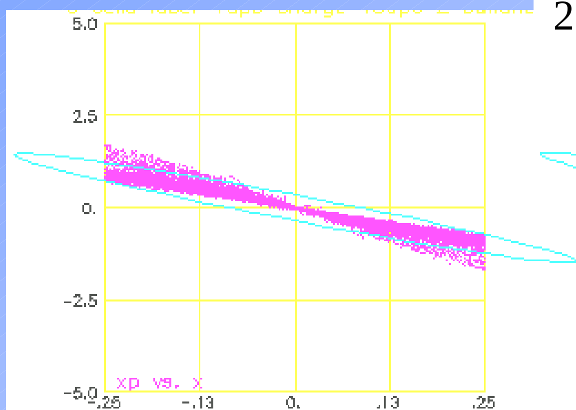




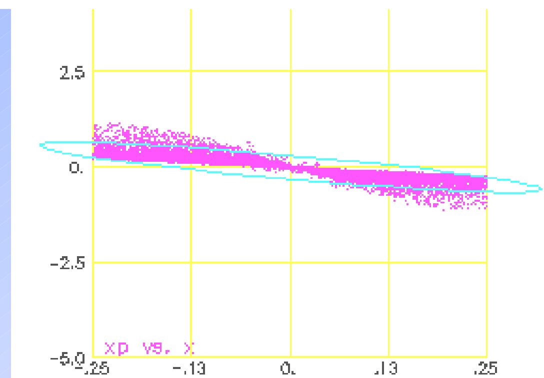
2.5 cell gun, 2 bunchers, 2 linacs

Energy=22.1, RMS(dkE)/kE=0.58%

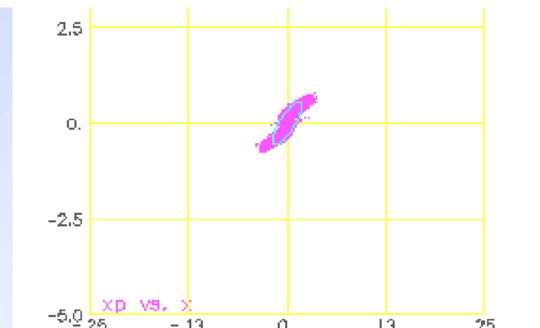
σ_z = 0.891 mm



Gun exit



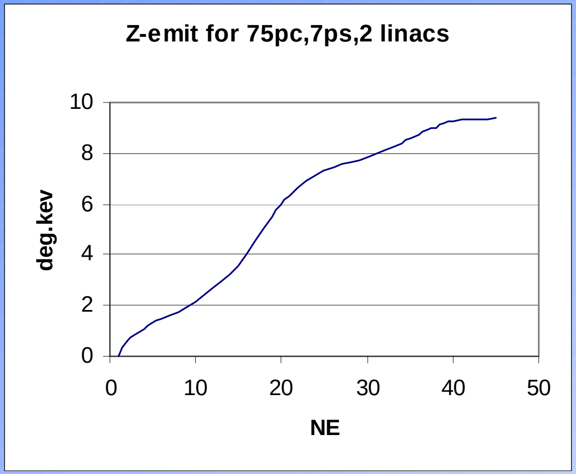
Buncher exit

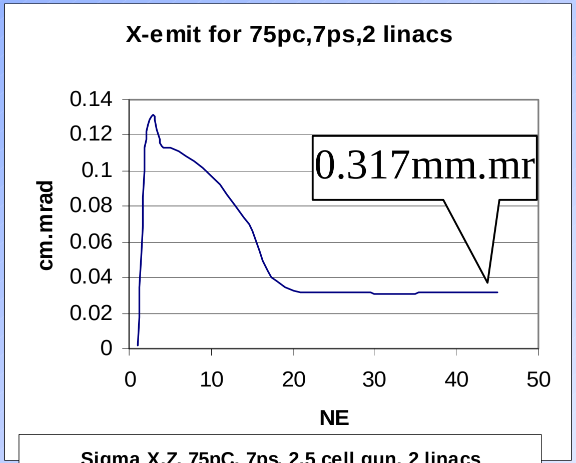


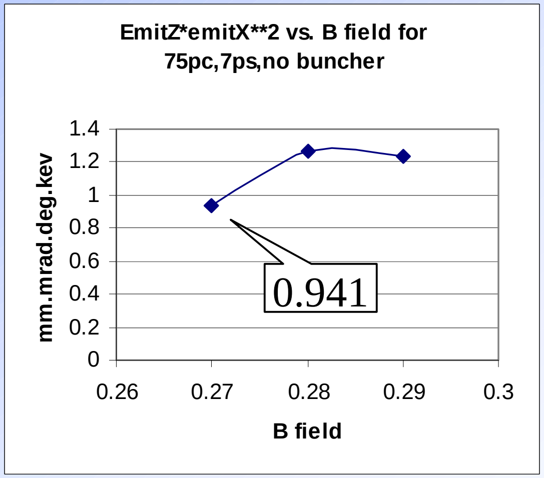
Linac Exit

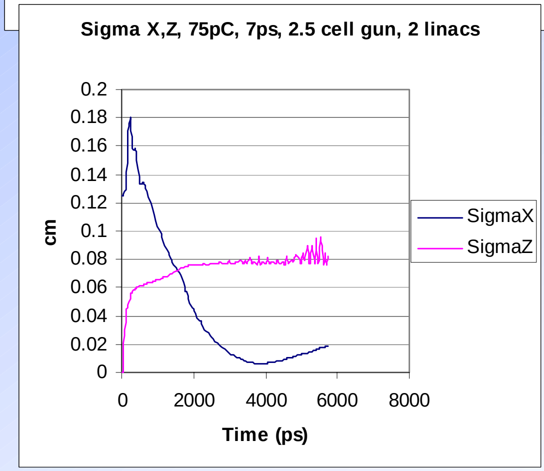
■ 75 pC, 7ps, 2.5 cell gun, no bunching cavity

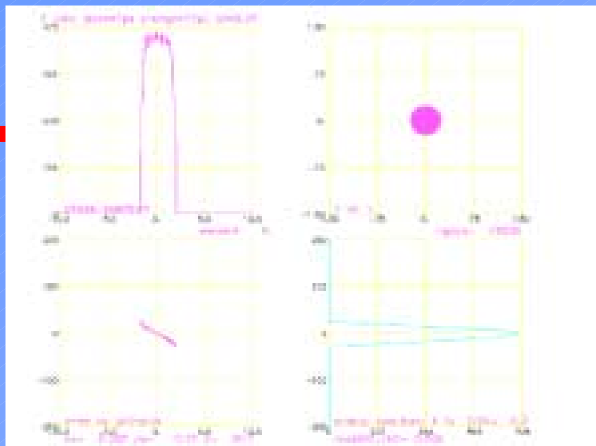
As space charge becomes lower, performance is much better, $\varepsilon_z \times \varepsilon_x^2$ is 1/7 that of 150pc. σ_z = 0.828mm,

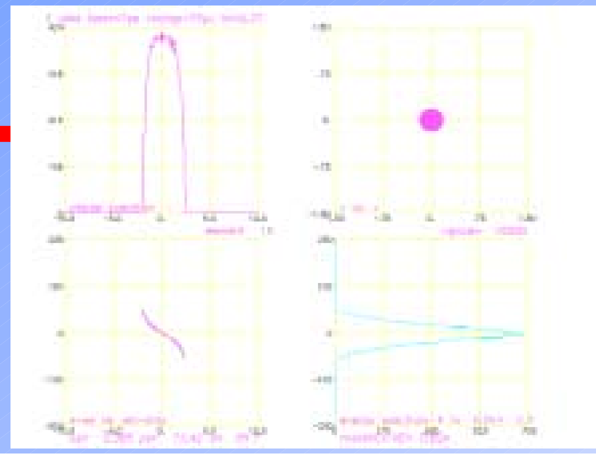


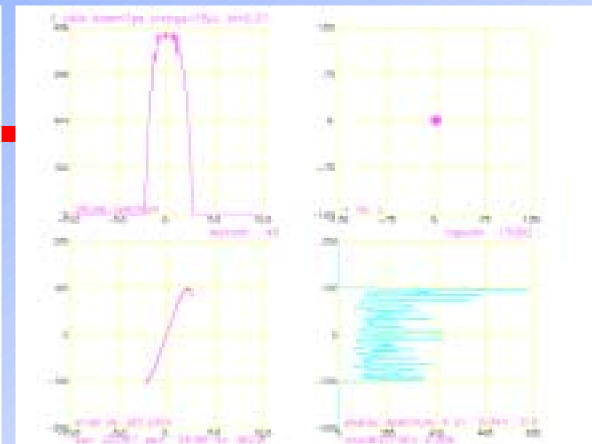








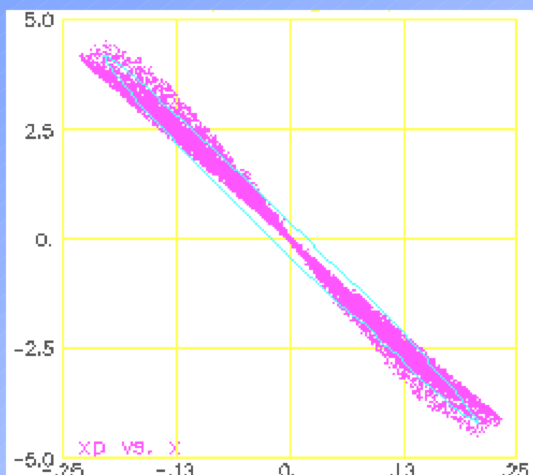




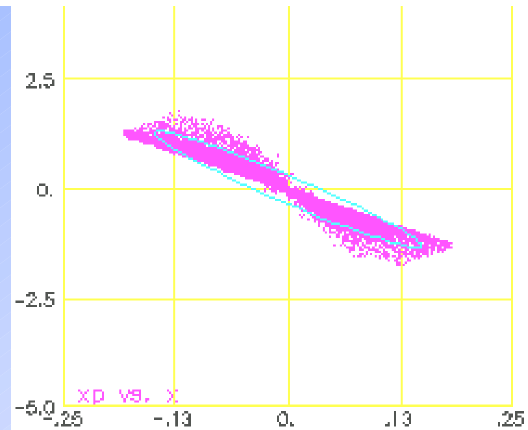
75pc,7ps,2.5 cell gun, 2 linacs

Energy=22.1, RMS(dkE)/kE=0.28%

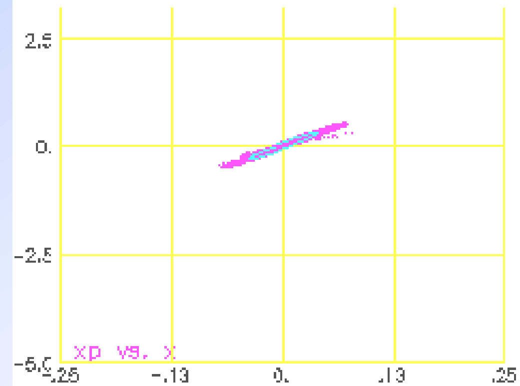
σ_z = 0.828mm



Gun exit



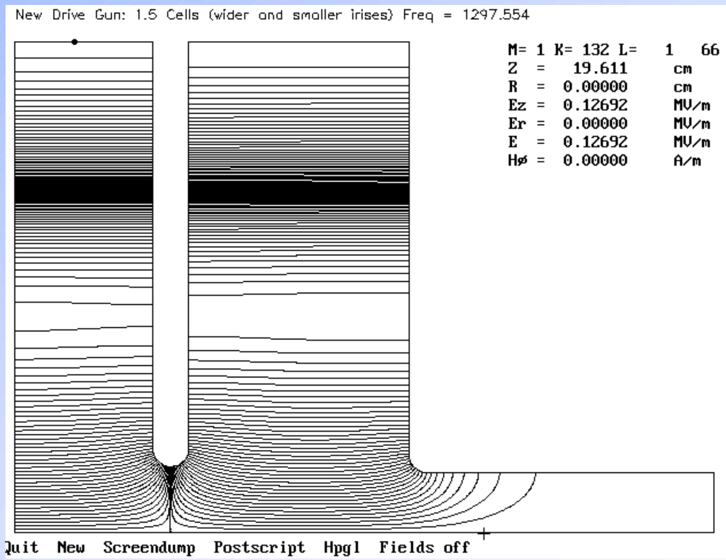
Linac entrance



Linac exit

■ Higher order mode cavity.

By using a gun working at high mode can increase its size. The total power loss on wall increases 60%, but the power dissipation density on wall decreases 60%, which can relieve the heat handling problem. As the field distribution is almost the same as original gun, beam dynamics do not change much. The problem is it will be difficult to apply enough solenoid field in gun because the diameter becomes larger.



Conclusion and Summary

- **L-band photocathode RF gun is capable of producing PERL quality beam.**
- **A 1.5 cell L-band with 25Mv/m can produce beam required by PERL**.
- **For a 2.5 cell gun, electric field on cathode 15Mv/m, and charge =150pC, we can reach at least the following beam performance at linac exit:**

Energy=21.9Mev, RMS(dkE)/kE=0.58%, σ_z*=1.24mm,*
ε_z*=22.8deg.kev,* ε_x*=0.545mm.mrad,*
$\varepsilon_z \times \varepsilon_x^2$*=6.775mm²*.*mrad²*.*deg.kev.*

- ***For a 75pC charge and 2.5 cell gun, no bunching cavity and longitudinal laser pulse shaping,***

Energy=22.1Mev, RMS(dkE)/kE=0.28%, σ_z*=0.828mm,*

ε_z*=9.364deg.kev,* ε_x*=0.317mm.mrad,*
$\varepsilon_z \times \varepsilon_x^2$*=0.941mm²*.*mrad²*.*deg.kev.*

- **Using higher mode cavity RF gun** can reduce the power density on the gun cavity wall. More geometric optimization could lead to power reduction 10%.

Conclusion and Summary

- More studies need to be done, such as:

  A. Performance of higher order mode gun.

  B. Study the possibility of shaping the cathode to increase RF focusing near cathode.

  C. Parameter optimization.

  D. Thermal stress and heat flow calculation are needed

Impact of Gun/Injector on PERL Beam Dynamics

J.B. Murphy

Ideal situation: Make 1.3 GHz rep rate, low charge, short bunches with little energy spread at birth in the gun and don't corrupt them!

Heat: Resistive wall, surface roughness, CSR, linac above cutoff

$$\text{Heat} \propto M\left(\frac{I_{ave}}{M}\right)^2 f(\sigma,\ldots)L$$

Comment: Short bunches will be tough in small gap IDs and less charge per bunch and more bunches is best!

RF Curvature Correlated Energy Spread:

$$V \propto \cos[\omega_{rf}t] \approx 1-(\omega_{rf}t)^2/2$$

Comment: Desire short bunches to reduce this effect.

Induced Correlated Energy Spread: CSR, resistive wall, surface roughness, linac above cutoff

$$\sigma_e \propto \left(\frac{I_{ave}}{M}\right)^2 f(\sigma,\ldots)L$$

Comment: Can't afford corruption of longitudinal emittance, less charge per bunch is best!

Wake Induced Emittance Growth: CSR & resistive wall

$$\Delta\varepsilon \propto \sigma_e\eta$$

Comment: Compressors may increase emittance.

PERL Injector Workshop Laser and Cathode Working Group Summary

Marcus Babzien,
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NSLS, BNL
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Introduction

In order to meet the general charge of developing the optimal electron source for a high average current, low emittance gun, the laser and photocathode must be considered together. The requirements set forth in these proceedings for a user facility specify beam stability and temporal shape, but it is the cathode material that determines the wavelength and power required from the drive laser. These fundamental quantities are the strongest determiners in choosing a laser system for PERL. For this reason, the laser and cathode are considered as one system by the working group. Therefore, design considerations of either the laser or the cathode will have direct consequences on the other.

Cathode Materials

The first task in developing a high average current electron source suitable for use in a DC or RF gun is to identify the various cathode materials and corresponding properties. These proceedings contain several talks on candidate materials, and a table of the most relevant parameters is shown below. This table provides a starting point from which to choose a cathode and make decisions on the laser systems that may illuminate them. To meet the goals of the meeting, it is necessary to make assumptions based on the experience of the participants, therefore the numbers shown in Figure 1 represent a best guess as to the state-of the-art performance of the different cathodes. Materials at much different levels of development are considered on an equal basis as far as basic parameters are concerned. Further conclusions taking into account the maturity of the different materials are presented at the end of this summary. The materials are broadly grouped into the Tellurides, Antimonides, Cesiated Gallium Arsenide, and a variety of lower quantum efficiency materials including Magnesium, Lanthanum Hexaboride, bonded, or other dispenser cathodes. Next, the required range of wavelengths at which the cathodes operate is given as a usable range, followed by lasers which can provide photons in this range, either directly or via harmonic generation. Typically, the variation in performance over these ranges is considered to be of secondary importance, although some of the wavelength dependence in emittance and quantum efficiency can be useful for optimizing performance. Next, the basic phenomena other than vacuum quality that affect the lifetime of the material are listed, but these are not very material specific. Other issues which deserve consideration are then listed for each material. These were issues that may limit the applicability of a cathode for PERL, but for which no good answers were known. Resolving some of these issues may require research and development. Next, the lifetime as demonstrated at initial fabrication and also more typical operating conditions are listed. Then, considering the wavelength and the PERL 200 mA current requirement, a the laser power for given quantum efficiency is given as a power*QE product. This demonstrates the basic advantage of the longer wavelength materials, especially GaAs. Expressed this way, an assumption in achievable quantum efficiency directly gives the amount of laser power required at the listed wavelength.

Some basic conclusions at this point are clear. The lowest quantum efficiency materials clearly involve a much larger effort to meet the PERL requirements than the other classes. This illustrates the tradeoff between cathode and laser, since the R&D effort required to produce a conventional, multi-100W UV laser system, which is beyond the current state-of-the-art, would be comparable to the effort required to incorporate either a parasitic or dedicated FEL amplifier to drive the photocathode. Such a conceptual design was presented at this workshop by A. Zholents. In addition, problems of laser heating, plasma formation, and cathode degradation may prove difficult to overcome for low quantum efficiency cathodes. As such, they should only be considered if other options fail.

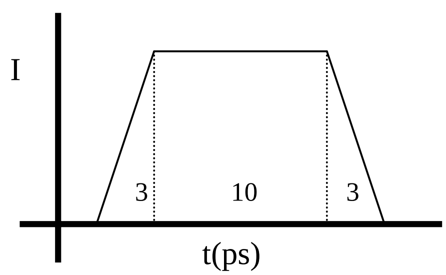
Type	**Cs_2Te CsKTe**	**Cs_3Sb K_2CsSb**	**GaAs**	**Metal Bonded LaB6 Dispenser**
Usable Photon Wavelength	260-300	350-600	780	UV
Laser Sources	Nd * 4 $Ti{:}Al_2O_3$ * 3 Argon * 2	Nd * 3 $Ti{:}Al_2O_3$ * 2 Argon	$Ti{:}Al_2O_3$ Diode * 2 Nd * 2 Argon	Seeded FEL
Lifetime Limiting Phenomena	All:	Chemical preparation	Ion bombardment	Preparation technique
Outstanding Questions	Usable in DC gun? (large thermal emittance) Code available?	Coating?	Ion Bombardment Limit?	Laser heat removal?
Best QE, Lifetime	24% @ prep 2%, 1 year @ 10^{-8}	14%, hours @ 10^{-10}	13-15%, 1-$1.2{*}10^5$ C/cm^2 @ $<10^{-11}$	0.3%, months @ 10^{-10}
Power*QE product	90 W·%	45 W·%	30 W·%	90 W·%

The best overall performance at this time is from GaAs, since it has high quantum efficiency, and operates at the longer fundamental wavelengths generated from common lasers. The applicability of this material to an RF gun is in question, primarily because of the high vacuum requirement. In addition, the ion bombardment mechanism that currently limits GaAs lifetime may work differently in an RF gun than DC gun. Therefore, GaAs is best used in a DC gun at gradients around 10 MV/m. In order to extend lifetime further, the vacuum level should be improved approximately one order of magnitude. If this is possible, then a quantum efficiency of 10% should be sustainable for the several hour lifetime required in PERL.

The second material that was considered a candidate for PERL is K_2CsSb. It has demonstrated very high quantum efficiency under operating conditions, although with short lifetimes. The major reason that the lifetime was not considered a major flaw was that very little effort has been focused on producing longer lifetime cathodes. The type of improvements reported for CsTe by D. Nguyen at this workshop may be achievable with K_2CsSb, however, this involves R&D into cathode preparation. Currently, the quantum efficiency that would be achieved in a PERL photoinjector is estimated to be 1%, and this was the design number used in the following sections.

Laser Designs

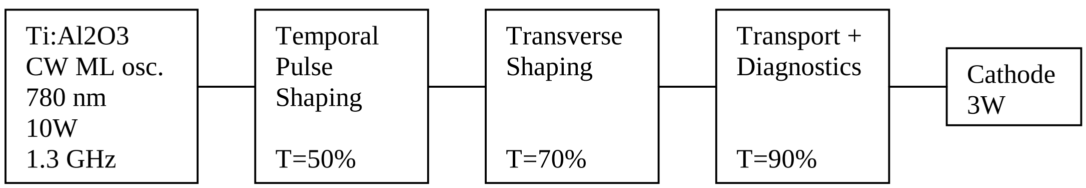
When developing rough configurations for the drive laser, a target power level is chosen for a cathode based on the quantum efficiency that is likely to be achieved after 24 hours of continuos operation. This means that the injector can be taken out of operation daily to switch either to a fresh cathode in the same injector, or a duplicate injector with a fresh cathode already in place. The final choice will depend on the speed with which a particular cathode can be replaced, the expense of injector duplication, and the impact of daily beam interruption on user experiments. It was assumed that this is the minimum acceptable operating cycle for PERL, but may be too short for some users. This also requires that the laser power compensate for changes in quantum efficiency over the 24 hour operating cycle. Under such assumptions, the laser requirements for the two candidate materials above are 3W at 780nm for GaAs, and 45 W @ 350 nm for K_2CsSb. A further assumption was that temporal shaping should be used to produce a laser pulse with 3 ps rise and fall times, separated by a 10 ps flat period, as shown below:



Also implicit in the following discussion is that any laser system will require feedback in intensity, phase and profile in order to meet the long term requirements for PERL. These feedback loops are not shown schematically, and would be expected to correct the long term drift as well as high frequency noise up to their bandwidth limit. The only parameter for which the feedback was deemed a possible weakness was in phase jitter. Although laser oscillators have demonstrated the required 200 fs rms value, no existing system has operated continuously and reliably at that level. Therefore it is considered to be at the limit of what can be achieved. For this reason, this requirement should be studied to determine if it presents a true limit for operation, or if slight degradation in laser performance is tolerable for some fraction of the time. Furthermore, some feedback systems may rely on instrumentation in the accelerator because sufficient sensitivity is not available from laser diagnostics located upstream of the photocathode.

Feedback is a necessary but not sufficient condition for satisfying the PERL stability requirements. The laser must be designed from the outset for highest possible stability. This includes environmental control for the laser room and all system components, power supplies and electronics. System performance should also rely as much as possible on physical mechanisms that maintain or enhance stability, such as gain or harmonic generation saturation. It is unlikely that a commercial vendor will have the experience necessary to design such a system. Although these considerations are as important as the choice of laser gain medium, they are assumed to be a critical part of the drive laser and will not be covered further.

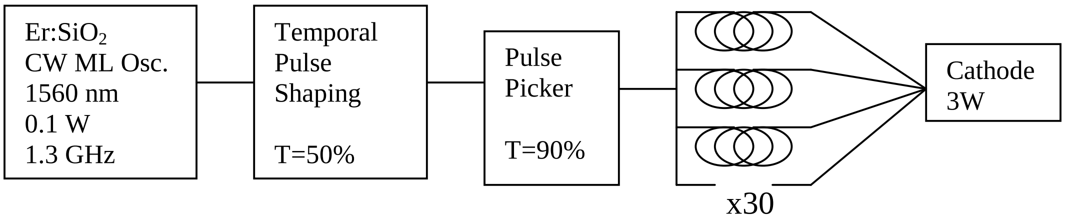
GaAs Cathode



The first suggestion for a laser is to use a high power Ti:Al_2O_3 oscillator directly. A 5W oscillator was reported at the workshop, and GHz repetition rates have been demonstrated, but not simultaneously. It should therefore be a modest extension of existing technology to achieve 10W CW modelocked in a single unit. The short pulses could then be converted to quasi-flattops either by Fourier-plane phase modulation, or direct time-to-space shaping, both of which have been demonstrated to have sufficient control. Some loss is encountered in either scheme, which we estimate as 50%. A further consideration arises not from the drive laser, but the delayed emission from GaAs that would limit the falling edge of the electron bunch to at least a 10 ps fall time. Following the temporal shaping, a spatial flattop is generated either by random phase masks, aspheric optics, and/or active mirrors. This stage may have transmission up to 70% if properly designed. Finally, it is assumed that delivery to the cathode will include losses simply due to extended distances or the harsh environment around a photoinjector, as well as multiple splitting for laser diagnostics. This loss is estimated as 10%.

One concern with this simple arrangement is the lack of control over the pulse format because no high power electro-optic modulator exists with sufficient bandwidth to operate at 1.3 GHz. This means that the beam current ramp-up required for PERL starting conditions must be accomplished exclusively by changing the laser energy per pulse, not the duty cycle. If this is not acceptable, it would necessitate a more complex scheme using lower power, integrated-optic, Mach-Zender interferometers followed by post-amplification. Also, the PERL requirement for ion-clearing by blanking approximately 100 ns of the pulse train every 2 us will be difficult with a simple oscillator configuration. It may be possible to develop a high repetition rate Pockels cell for this function, but no participants were aware of demonstrated devices with this capability.

A second laser option for 780 nm was identified based on fiber oscillators already demonstrated.



Such erbium-doped fiber oscillators are common in telecommunications applications, and are typically characterized by extreme phase and power stability. GHz repetition rates are achievable, with up to 100mW unamplified power. The temporal pulse shaping could be accomplished with the same techniques as above, and material bandwidth is sufficient for sub-picosecond shaping. There is some concern that shaping may be more complicated because of the non-gaussian gain spectrum when compared with Ti:Al_2O_3, and this may necessitate spectral filtering and reduced gain. Following temporal shaping, a GHz bandwidth pulse picker can be used to generate arbitrary trains to satisfy the PERL ramp-up and ion-clearing requirements. An assumption was made that high power fiber amplifiers may not be available, although greater than 10W has been demonstrated is research lasers. A conservative estimate of 200 mW per fiber would require over 30 individual amplifiers, assuming 50% conversion efficiency from 1560 to 780 nm. This conversion efficiency is routine using periodically poled lithium niobate. In this laser system, the total output of all the amplifiers could be angle-multiplexed onto the cathode. The beam profile achievable with such a configuration may be non-uniform, or depending on the geometry of the electron, may have too large a divergence angle to project to the cathode.

Another fiber-based scheme would start with a similar erbium oscillator, with the output Raman-shifted to 1.06 um. Such a system has been demonstrated with up to 1W, and higher powers are not limited by the fiber amplifier. Hence extrapolating to several watts should not be difficult. This would allow a single, diffraction limited output beam to be used for transport to the cathode.

K_2CsSb Cathode

The most attractive system for achieving the higher average power in this case may be the Raman-shifted fiber source, as it can be coupled to bulk amplifiers capable of multi-100 W output near 1060 nm. Frequency conversion would likely be the critical factor in deliverable power as efficiency may be limited by a combination of average and peak power crystal damage. At 1.3 GHz and 15 ps, the peak power enhancement would be a factor of 50, and very little data is available on damage thresholds in this regime. If it is possible to reach saturated conversion, third harmonic generation of 45W should be achievable. Reduced intensity and conversion efficiency could be overcome with higher amplification. Another option is be to use the second harmonic instead of the third. Although the quantum efficiency is about 30% higher at 350 nm compared with 530 nm, this may be offset by a higher doubling efficiency. Only by testing the different nonlinear crystals involved, and the damage thresholds for the PERL pulse format, will data become available for selecting the best scheme.

Conclusions:

Because of the relatively small amount of effort that has gone into developing improved lifetime in K_2CsSb, the high quantum efficiency, and visible operating wavelength, this is a very promising candidate for further study. Techniques for extending lifetime are improving operating vacuum in the gun, and using cathode protective coatings. As demonstrated at Los Alamos, large improvements in cathode robustness are possible with a modest research and development effort. Therefore, cathode development appears to be the most fruitful area for further research. Should there be little or no improvement in lifetime, a greater effort could be placed into laser development to reach the necessary power. Finally, within the limitations noted above, the existing performance of GaAs indicates that it may already be a usable photocathode in a DC gun, and represents a fallback option.

Photocathode and DC Gun Summary

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Before discussing DC guns, it is necessary to provide some overview of the cathodes which would be used in these guns (or in RF guns for that matter). The first point is to recognize that only high quantum efficiency photocathodes can be considered to meet the PERL parameters. For any linear photoemitter, the following relation between the laser power P and wavelength λ, the cathode quantum efficiency, and the photoemission current is true.

$$i(mA) = \frac{\lambda(nm)}{124} \bullet P_{laser}(W) \bullet Q.E.(\%)$$

There are three families of practical high quantum efficiency photocathodes – the alkali antimonides, the alkali tellurides, and the III-V semiconductors. The first two of these families have positive electron affinity (PEA), while the III-V semiconductor cathodes offer negative electron affinity (NEA). The importance of this distinction will become apparent later. One can make a simple summary of these three families, giving the typical operating wavelength, and the product of laser power and quantum efficiency necessary to reach the required 200 mA specification for PERL. This table makes it very clear that the lasers necessary are very demanding even for a 1% Q.E. photocathode. Photocathodes with Q.E.'s lower than about 1% are very unlikely suitable for application in a high average current PERL photoinjector.

Cathode Type	Typical Operating Wavelength (nm)	P_{laser} x Q.E. (w-%)
GaAs (NEA)	780	31.8
K_2CsSb (PEA)	532	46.6
KCsTe (PEA)	266	93.2

It should be noted that all of the above lasers are assumed to have an appropriate RF time structure (e.g. suitably short duration pulses at a 1300 MHz repetition rate for

PERL), and that the P x QE numbers assume that every electron and every photon is useful. Thus, for example, if a Gaussian laser beam is truncated transversely to more closely approximate a "tophat" profile, or if some electrons are removed early in the injector, a higher P x QE product will be required.

One can inquire about the thermal emittance produced by each of the above cathode families. For our purposes, we write the normalized, rms emittance as:

$$\varepsilon_{n,rms} = \frac{r}{2}\sqrt{\frac{E_{thermal}}{mc^2}}$$

Thus, for example, if a cathode emits electrons from a Maxwell-Boltzmann distribution characterized by a temperature T, the thermal energy in the above expression is simply kT. The above expression is known to give a good description of the emittance from a thermionic cathode.

In the case of GaAs photocathodes, the absorption coefficient for light at ~ 780 nm is about 1.4/μ. This leads to a half absorption depth of about 500 nm. Electrons photoexcited into the conduction band of GaAs have almost completely thermalized at the bottom of the conduction band by the time they diffuse to the surface of the cathode. Since GaAs is a negative electron affinity cathode, electrons at the bottom of the conduction band may energetically escape the cathode. Thus, the GaAs photocathode should produce an emittance characterized by a thermal energy close to the cathode temperature – i.e. room temperature in most cases. That this is indeed the case has been demonstrated by Bruce Dunham in his Ph.D. thesis, (B. Dunham et al., 1995 PAC, p. 1030). Dunham measured that an emittance containing ~ 95% of the beam from a GaAs photocathode was characterized by a thermal energy of about 35 meV (n.b. room temperature is 25 meV). Dunham's measurements were conducted with a DC beam having a tophat transverse laser profile at the cathode. His measurements were made for a number of spot sizes and illuminating wavelengths. It is worth mentioning that the negative electron affinity GaAs photocathode is being evaluated for e-beam lithography applications. In this application, the beam brightness is very important. A recent paper (Mankos et al., JVST B18, 3010 (2000)) reports an effective temperature for a GaAs cathode of 0.05 +/- 0.02 eV, in agreement with Dunham's values. Also, measurements made on the injector for the CEBAF accelerator are in agreement with Dunham's values. In this latter case, the laser had an RF time structure (~ 45 psec FWHM duration pulses at 499 MHz repetition rate) and a Gaussian transverse profile.

Similar quality measurements of the emittance produced from alkali antimonide and alkali telluride photocathodes have not been reported (to the best of this writer's knowledge). However, since these cathodes have positive electron affinity, it is not energetically possible for electrons thermalized at the bottom of the conduction band to escape. Thus photoemission from these materials is from a non-thermal electron population. The optical absorption in these cathodes is much higher than in the case of GaAs – a typical absorption coefficient is about 30/μ. Thus, the half absorption depth is about 23 nm. One would expect that the photoemitted electrons would have a spectrum of energies ranging from about zero up to the energy difference between the exciting photon and the work function. Few measurements of this quantity have been reported, but numbers in the literature range between 200 and 600 meV for alkali antimonide cathodes. Alkali telluride cathodes have a smaller electron affinity than alkali antimonides, and thus might be expected to have a somewhat smaller effective thermal energy. At the workshop, numbers of 200 to 300 meV for these cathodes were mentioned.

Two additional points should be made. First, the relatively low optical absorption in GaAs means that very short duration (few psec) electron pulses cannot be delivered, since most of the emitted electrons must diffuse to the cathode surface from some depth within the cathode. Shorter pulses can be obtained from GaAs photocathodes by reducing the illuminating wavelength, but this comes at the cost of higher thermal energy. The alkali antimonide and alkali telluride cathodes, with much higher optical absorption, are able to support the delivery of much shorter duration electron pulses. Second, in some future application of the GaAs source, it might be practical to produce even lower thermal emittance by cooling the cathode, thus allowing the conduction band electrons to thermalize to a lower temperature. In fact, the first GaAs photoemission electron gun ever used on an accelerator had a cathode operated at liquid nitrogen temperature (though this was not done for thermal emittance reasons). While this did make the gun more complicated, it was nevertheless quite practical. Measurements of the energy spread of the beam produced from a GaAs photocathode show the expected reduction with lower temperature (C. S. Feigerle et al., Appl. Phys. Lett. 44, 866 (1984); H.-J. Drouhin et al., Phys. Rev. B 31, 3859 (1985)).

For PERL applications, the emittance which matters is the geometric emittance at the insertion devices. This can be translated back to the emittance provided by the injector, which in turn is composed of two parts – the thermal emittance from the cathode and the space charge related emittance growth which occurs between the cathode and the beam energy at which the electron bunches are sufficiently rigid that further emittance growth is negligible (assuming that effects like wakefields, coherent synchrotron radiation, etc. are limited or controlled). Once one has an injector design and understands the details of the emittance growth, the maximum allowable thermal emittance from the cathode can be specified. This number is directly related to the electric field that must be present at the cathode.

To hold space charge related emittance growth to tolerable levels, one can remove only a fraction of the charge stored on the cathode surface due to the cathode electric field. Given a thermal emittance that cannot be exceeded, one knows the maximum cathode radius that can be illuminated. This, in turn, establishes the cathode field that must be present to provide the required bunch charge without excessive space charge effects. The GaAs cathode, having the lowest value for the effective thermal energy, will allow the largest illuminated diameter, and thus may be operated at the lowest cathode field. The positive electron affinity cathodes, having a higher effective thermal energy, will require a smaller illuminated spot, and thus a higher cathode field, to achieve the same performance.

At Jefferson Lab, we operate DC photoemission guns with GaAs cathodes for both the CEBAF accelerator, and the FEL. The CEBAF electron source operates at 100 kV with a maximum average current of about 200 μA, while the FEL operates at 320-335 kV with a maximum average current of 5 mA. Although the FEL gun has been processed to ~ 550 kV, it is operated at lower voltage due to field emission problems. This field emission arises from the fact that the cathode is prepared in situ in the gun. Cathode preparation involves the use of cesium, which lowers the work function of the cathode electrode structure. A gun re-design that eliminates this problem is underway. An upgrade to the FEL is under development, and will involve operation at 10 mA average current. We are confident that by eliminating the introduction of cesium into the gun structure, we will be able to operate this gun at its design value of 500 kV.

The operational lifetime of the GaAs cathodes used in the two guns above is limited only by ion back bombardment. These ions are produced by the beam ionizing residual gas molecules in the cathode-anode gap, and are accelerated back to the cathode, where they cause reduction in the QE by a variety of phenomena. Given that ion back bombardment is the lifetime limiting phenomenon, it makes far more sense to express the cathode operational life in terms of the number of coulombs delivered per unit illuminated area, rather than clock hours. Indeed, the 1/e lifetime of a GaAs cathode simply sitting in the static vacuum of one of the JLab nuclear physics guns was measured to exceed 2.3 years. In service with beam delivery, the best 1/e operating lifetimes we have yet obtained are between 1 and 1.2 x 10^5 coulombs/cm^2. It should be noted that the ion back bombardment problem will be different, and probably less severe, in a RF gun.

At JLab, we have demonstrated that with a heat treatment and reactivation, we can fully recover the initial quantum efficiency of an ion bombardment damaged GaAs cathode. The number of times this operation can be successfully performed is not well known at present, but it is large. We have achieved further extensions of the practical cathode operational lifetime by illuminating a number of small area spots on a much larger area cathode. In the DC gun case, moving the laser beam spot on the cathode requires only a simple re-steering of the electron beam exiting the gun, which is done by a fast, automatic routine on the CEBAF injector. This technique may not be so easy to employ in a RF gun, where one wants to operate with beam on the electromagnetic axis of the cavity.

In contrast to the GaAs cathode, which is formed by adding a single cesium – oxygen or cesium – fluorine monolayer to the GaAs surface, the alkali antimonide and alkali telluride cathodes are stoichiometric chemical compounds. It is not unreasonable to assume that these cathodes may behave quite differently under ion back bombardment. Furthermore, since the light is absorbed in such a short distance in these cathodes, most of the damage done by ions is likely to lie deeper in the cathode material than the region from which the photoemitted electrons originate. Indeed, Nguyen from Los Alamos reported a lifetime of 8×10^6 coulombs/cm^2 for a Cs_2Te cathode operated in a moderate voltage DC gun – almost two orders of magnitude higher than the best numbers reported for GaAs.

It is possible to make high quantum efficiency cathodes from all three cathode families. At the wavelengths indicated in the table above, quantum efficiencies between 10 and 20% have been reported for all cathode types. However, only the GaAs cathode has been used in DC guns, while the antimonide and telluride cathodes have been used in RF guns. The antimonide and telluride cathodes are prepared in vacuum chambers external to the RF gun structure, and then inserted into the RF gun with an in-vacuum transfer mechanism. Although these cathodes have good lifetimes in the static vacuum of the preparation chambers, they were all reported to lose quantum efficiency fairly rapidly on insertion into a RF gun. These cathodes were reported to stabilize at quantum efficiencies between ½ and 2%, at which point they operate stably for extended periods of time. By contrast, the GaAs cathodes reported on are actually formed in situ in the gun, and their dark lifetime in the gun is excellent.

The difference in QE stability is no doubt largely due to the vacuum conditions in the gun. This is one area where a DC gun has an advantage. One has great freedom in choosing the vacuum wall material, the wall location, and the location of ports in a DC gun. In a RF gun, one has a very limited choice of wall material, a wall geometry constrained by the realities of a resonant cavity, and great restrictions on the location and size of ports.   Thus, it will likely always be true that it is much easier to establish an excellent vacuum in a DC gun than in a RF gun.

The limiting phenomenon in the cathode field strength and operating voltage of a DC gun is field emission. Field emitted electrons may collect on the ceramic insulator that holds off the primary gun voltage. Unless this charge is drained away, punch-through of the ceramic may occur. Even if the ceramic is protected from this problem, field-emitted electrons striking chamber walls release gases through electron stimulated desorption. Such gases are harmful to the cathode lifetime, either through chemical poisoning of the cathode, or by providing a source of residual gas that can lead to ion production.

Recent developments have made major advances toward resolving both of these issues. First, an LBL/Jefferson Lab group has developed a metal ion implantation process which produces a high resistivity sheet resistance on the vacuum surface of large ceramic insulators (F. Liu et al., PAC ’97, p. 3752). Ceramics treated this way have been very successfully used in the Jefferson Lab FEL gun. More recently, a Jefferson Lab group has shown that plasma-source nitrogen ion implantation of large area metallic electrodes dramatically reduces the field emission up to quite high fields. Field emission as low as 0.5 pA/cm^2 has been measured at DC fields above 25 MV/m (C. Sinclair et al, abstract submitted to PAC ’01). With the benefits gained from these two separate ion implantation processes, it now appears to be within reach to build DC electron guns operating reliably with cathode fields at or above 20 MV/m. DC power supplies to support the high average current at the high DC gun voltage have been developed by several manufacturers (W. Scharf and W. Wieszczycka, AIP Conference Proceedings No. 475, J. L. Duggan and I. L. Morgan, eds. American Institute of Physics, 1999).

A note regarding the drive laser for a GaAs gun is worth making. To produce the necessary RF time structure on the laser beam, some form of mode locking is employed. In most mode locking schemes, the optical cavity round-trip time must be equal to the desired RF period. At 1300 MHz, the resulting cavity length is impractical, leading to designs which use a lower mode locked frequency followed by various schemes to produce the desired 1300 MHz pulse train. There are real issues of long term stability with such systems. Recently, a Ti:sapphire laser mode locked by gain modulation has been developed at Jefferson Lab (C. Hovater and M. Poelker, NIM A 418, 280 (1998)). The fundamental frequency of this laser is typically about 225 MHz. It is easy to obtain stable mode locking at multiples of the fundamental frequency up to several GHz (2.5 GHz has been demonstrated). The output power is independent of the RF frequency, and is quite high. A laser of this type has been in routine service on the CEBAF accelerator photoinjector since August, 2000. It is worth noting that this laser operates stably 24 hours/day with no active feedback loops to stabilize any parameter – including the cavity length. A 2.5 W version of this laser has been demonstrated at Jefferson Lab, and we believe that this technique can be scaled to about 10W without significant problems. We also note that high average power amplification of a high frequency optical pulse train from a Ti:sapphire laser has been demonstrated at the 5.77 W level (Z. Liu et al., Appl. Phys. Lett. 76, 3182 (2000)). It appears that a ~ 10 W average power laser, operating at 780 nm and 1300 MHz repetition rate should be well within reach.

Another issue that should be noted is that of energy deposition in the cathode material. For example, suppose one has a 2% QE Cs_2Te cathode illuminated at 266 nm. 46.6 W of laser power is required to deliver 200 mA average current. If we require a thermal emittance of 0.5 micron, and assume that we have a "tophat" transverse beam profile, the allowable illuminated radius is 1.43 mm. The absorption coefficient of Cs_2Te is about 30/μ, so that half the incident light is absorbed in a depth of 23 nm. The optical power deposited in the cathode in this case is over 150 MW/cm^3. While it is clear that such a cathode would have to be formed on a thermally conductive substrate, this is a prodigious power density, raising questions about the durability of the cathode.

In summary, we can say at the outset that the selection of the cathode type will have a very direct bearing on the design of the rest of the system. If a DC gun is chosen, there is a good opportunity to create a very excellent vacuum. In a RF gun, creating such a vacuum is more problematic, though it is not clear that much attention has been focussed on this issue to date. The primary problem with DC guns is field emission from the electrode structures. Recent developments in ion implantation have shown considerable promise in creating a highly resistive inner surface on the ceramic insulators, preventing charging from field emitted electrons, and on dramatically reducing the field emission from the primary electrode structures. It appears that DC electron guns operating with cathode fields in the 20 MV/m range may be developed in the near future.

The GaAs cathode offers the prospect of very low thermal emittance, since the electrons originate from a thermal population at close to room temperature. At some stage in the development of very bright electron sources, the thermal emittance must be considered along with the emittance growth associated with space charge and other effects. Lasers with 1300 MHz RF structure and adequate power to provide 200 mA average current from a GaAs cathode are only a modest extrapolation of what has already been demonstrated. A GaAs cathode, operated in a state-of-the-art DC electron gun is surely a contender as a high brightness, high average current electron source for PERL type applications.

Conclusions of the 433 MHz / B-Factory Cavity Based RF Gun Working Group

D.H. Dowell, Chair
Working Group Members: R. Rimmer (LBNL), P. Piot (DESY), W. Gai (ANL), J-P. Carneiro (FNAL), I. Ben-Zvi (BNL), X.Y. Chang (BNL), H. Edwards (FNAL) J. Rose (BNL).
Since the 433 MHz working group had combined discussions with the 1300 MHz group, this summary includes comments related to the 1300 MHz photoinjector.

Executive Summary:

The 433 MHz photocathode gun technology is the most advanced of the three approaches discussed in this workshop. Essentially all the PERL photocathode gun performance requirements of high average current operation and beam quality are met either experimentally or by simulation. In addition, the overall architecture of the photoinjector up to injection into the SRF (approximately 25 MeV) is well-established. Therefore this approach has the lowest technical risk of the three photoinjectors being considered for PERL.

The 433 MHz gun working group, and the workshop participants in general, conclude the single disadvantage of the 433 MHz photoinjector is the high microbunch charge needed to generate 200 mA of average current. The charge is three times that of the 1300 MHz gun. Combined with the PERL specification for short, sub-ps microbunches, this high charge will strongly radiate in the high-energy bends, leading to significant degradation of the beam quality. However, it should be noted that the 1300 MHz photocathode gun has been operated only to 1% duty factor vs. 25% operation for the 433 MHz gun. In addition, the closely spaced microbunches (769 ps) of the 1300 MHz pulse train may experience more severe transverse wakes than the more widely separated (2.3 ns) 433 MHz pulse train. These and other issues require further study before deciding which frequency is best for PERL.

A concise list of the working group's recommendations follows:

1. Third-harmonic linearizer is required for either frequency.
2. Develop the high-QE K_2SbCs photocathode. Incorporate concepts presented in workshop for increasing cathode lifetime.
3. Further investigation of all wakes (CSR and resistive wall) is essential to decide between 433 and 1300 MHz approaches. It is preferable that the wakes be realistically included in the beam transport simulations.
4. Realistic simulation of entire 1300 MHz-based system. Include the much lower beam energy out of the cathode cell in the calculation. What can be used for the CW booster and 3.9 GHz linearizer accelerator sections? The single pass beam current is probably too high for a SRF booster.
5. Model energy recovery dynamics. Investigate RF-beam instabilities.
6. Review overall PERL architecture. Compare co-propagation vs. anti-propagation in energy recovery linacs to control beams with large energy differences.

Photoinjector Architecture

The photoinjector layout from the gun to injection into the SRF was show by D. Dowell. It consists of the RF gun, a 433 MHz booster, a 1300 MHz linearizer and a chicane compressor. Experimental results demonstrating improved compression with the third harmonic linearizer were shown.

In an earlier session, P. Piot discussed how the linearizer eliminates CSR-induced beam breakup, and pointed out that DESY is interested in collaborations to develop a 3.9 GHz. SRF linearizer cavity.

RF Design

R. Rimmer presented details of the 476 MHz B-factory cavities and how they could be adapted to 433 MHz for the gun and booster sections. These cavities have already demonstrated CW operation at the required beam currents, and present little technical risk.

D. Dowell presented details of the Boeing 433 MHz RF gun and APLE (Average Power Laser Experiment) booster cavities. The RF gun has successfully run at 25% duty factor, but will require some modification for CW operation. The CW APLE cavities are copper-plated aluminum and are available in 3-cell and 5-cell configurations.

A single Tesla SRF cavity can be used for the linearizer.

Photocathode

The photocathode choice has major implications for the drive laser. A high-power, UV drive laser, as required for Te_2Cs, is considered to be technically risky. GaAs is attractive from the drive laser's point of view, but requires the best vacuum of all the cathodes and has poor temporal response. Therefore the group decided that K_2SbCs is the only option for PERL.

Consider the following situation for PERL. The K_2SbCs cathode lifetime decays exponentially. Assume an initial QE_i of 12% (14% has been demonstrated) and that the drive laser power is sufficient to produce the required charge at a 1% final QE_f. Then the lifetime (LT) needed to operate T_{op} hours is given by,

$$LT = \frac{T_{op}}{\left(\ln \frac{QE_i}{QE_f} \right)} .$$

Therefore 24 hours of operation requires a lifetime of 9.6 hours. Lifetimes of 2.3 hours were demonstrated in the 1992 25% duty factor tests at Boeing. Therefore current technology is only a factor of five below PERL requirements, ignoring any improvements in the gun vacuum.

Techniques for greatly improving the lifetime were presented. These include coating with a thin protective layer of CsBr (presented by D. Nguyen, LANL in an earlier session) and operating the cathode at an elevated temperature to keep it clean. Experiments give a lifetime in excess of 20 hours for a cathode at 120 degrees C. in a poor vacuum, and therefore could easily meet the PERL specification. An automated, multi-cathode system incorporating these ideas should be considered.

To produce 0.5 nC of microbunch with a 1% QE cathode means the drive laser produces approximately 0.1 microjoule per microbunch at a repetition rate of 433 MHz or 43 watts CW at 527 nm. This should be possible. The drive laser developed by LANL for the 1992 Boeing 25% duty factor test operated with 0.47 microjoule per microbunch at 27 MHz. The 8.3 millisecond macropulse power was 12.7 watts, the average power was 3.2 watts.

Recommendations

The third harmonic linearizer is required at any photoinjector RF frequency. Detailed simulations of CSR and resistive wall wakes, both transverse and longitudinal, are needed since this will be a major factor in choosing between 433 and 1300 MHz guns. More effort is needed on the 1300 MHz injector to answer questions concerning the availability of a CW booster and a 3.9 GHz linearizer. The single-pass beam current maybe too high for a SRF booster.

The K_2SbCs cathode technology should be developed to allow the use of a visible wavelength drive laser. This effort should start soon since the cathode choice places major design requirements upon both the drive laser and the RF gun vacuum. In the longer term, an automated, multi-cathode should be developed.

In conclusion, the 433 MHz photoinjector is the most developed of the three injectors discussed in this workshop. Its sole disadvantage is the 200 mA average current requires the high-charge microbunches, which strongly radiate in the beam transport system when compressed to sub-ps bunches.

Summary of L-band Working Group

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We have examined the L-band option for PERL in this working group. Some comparisons were made with 433 Mhz option. There were 4 talks given for preliminary design studies. The summary is given below.

The starting design point is the ANL 1 ½ cell L-band gun. With modified parameters, 1 ½ TM02 mode operation and 2 ½ cell options were also examined [X.Y. Chang]. From the beam dynamic point view, L-band would provide higher brightness beam at lower charge per pulse which is crucial for beam transport in bends (Coherent Synchrotron Radiation wakefield reduction). CSR can be very severe in beam transport, particularly beam pulse length compression using a chicane as experimentally verified by Ph. Piot. They observed beam energy bifurcation due to CSR at 130 MeV. It is believed that the six phase space parameters can be obtained using different L-band options as discussed above.

During the discussion, Bob Rimmer presented their work on the heat load at LBL. He suggests that 100 W/cm^2 is a limit for current operation. However, he also considered a few times of that maybe achievable. Another import result obtained through the discussions, is whether the L-band will be much worse than the 433 MHz structure. Bob Rimmer and Ilan Ben-zvi came to a conclusion that heat generation density in L-band is comparable to that of the 433 MHz using a scaling law.

We have also discussed the liquid nitrogen cooling option for the PERL gun. However, because there is no any experimental data available to date, we have to speculate how to cool the acceleration structure. Two options were discussed: 1) Single phase liquid cooling and 2) Two phases (liquid and gas) cooling. Advantages using liquid nitrogen as coolant are identified: 1) lower the RF power consumption; 2) increased heat conduction; 3) improved vacuum condition (no water residues) would improve cathode life time; and 4) sustain higher gradient in the gun than at normal temperature. Due to the attractive of liquid nitrogen option, we recommend some engineering research should be started right way.

Different RF photocathodes were considered, the conclusion is that we already have technologies may be not two far from the PERL requirements. Cathode lifetime and QE can be overcome by using hot standby spares. It was recommended by the working group that a lab should be setup to study the QE issues such as lifetime and vacuum conditions.

L-band RF power supply for 1 – 2 MW CW source is already available at Toshiba. We believe this is adequate for the PERL gun and booster applications.

One concern was raised and discussed but we were unable to get any answer is beam break up in the gun and booster. The average current in the PERL is 20 times higher than TESLA operation, therefore a serious beam break up problem may arise.

Workshop on Photo-injector for Energy Recovery Linac
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PERL Injector
Summary and Future R&D direction

Our studies show that, it is feasible to build a photoinjector for PERL. Based on our studies and recommendations from PERL injector workshop, future PERL injector R&D plan:

1. Start cathode experimental program immediately.

A. Visit other facility.

B. Engineer design of cathode test stand.

C. Start purchase long lead time items for the cathode test stand.

2. Focus on L-band Injector studies:

A. Thermal analysis of the heat load of the RF gun cavity.

B. Engineering analysis of LN cooling feasibility.

C. Beak breakup and other beam dynamics studies of boost linac in collaboration with Beam Dynamics Group.

3. *Establish Injector test facility*

Funding and Support Request

- Travel funding: $6k.
- One engineer and one designer working on cathode test stand design.
- One engineer working on thermal analysis of the RF cavity.
- One posdoc and one graduate student work on the design studies.
- Capital money for long lead item purchase.

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